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Volume 1. User's Instructions

TRC Environmental Consultants, Inc., Mountlake Terrace, WA

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FDM

Fugitive Dust Model

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This document provides a technical description and user's instructions for the Fugitive Dust Model (FDM). FDM is a computerized Gaussian-plume air quality dispersion model, specifically designed for estimation of concentrations and deposition impacts from fugitive dust sources. The sources may be point, line, or area sources. FDM employs an advanced gradient-transfer particle deposition algorithm. Gravitational settling velocity and deposition velocity are calculated by FDM for each of up to 20 user-specified particle size classes. Descriptions of three performance evaluations of FDM and the EPA Industrial Source Complex model are included in an appendix. Also included with the manual is a floppy diskette containing FORTRAN source codes, PC executable codes, and test data sets.

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USER'S GUIDE FOR THE FUGITIVE DUST MODEL (FDM)
(revised)

Volume I: User's Instructions

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3

TABLE OF CONTENTS

Volume I: User's Instructions

1.0 INTRODUCTION.. 1

2.0 TECHNICAL DESCRIPTION........................... 3

3.0 USER'S INSTRUCTIONS............................. 21

4.0 VALIDATION/SAMPLE RUNS.......................... 39

REFERENCES.. 41

APPENDIX A: VALIDATION STUDIES

APPENDIX B: SAMPLE INPUT/OUTPUT RUNS

APPENDIX C: RELEVANT SECTIONS FROM THE CALINE3 USER'S GUIDE

Volume II: Computer Program Listing

APPENDIX D: COMPLETE LISTING OF THE FDM COMPUTER PROGRAM

1.0 INTRODUCTION

The Fugitive Dust Model (FDM) is a computerized air quality model specifically designed for computing concentration and deposition impacts from fugitive dust sources. The sources may be point, line or area sources. The model has not been designed to compute the impacts of buoyant point sources, thus it contains no plume-rise algorithm. The model is generally based on the well-known Gaussian Plume formulation for computing concentrations, but the model has been specifically adapted to incorporate an improved gradient-transfer deposition algorithm. Emissions for each source are apportioned by the user into a series of particle size classes. A gravitational setting velocity and a deposition velocity are calculated by FDM for each class. Concentration and deposition are computed at all user-selectable receptor locations.

The model is designed to work with pre-processed meteorological data or with card-images of meteorological data either hourly or in STability ARray (STAR) format. FDM accepts hourly meteorological data output from the EPA RAMMET meteorological pre-processor program. In addition to a standard printed output, the model allows a "plotter" output file which consists of a series of records containing only the x-coordinate, the y-coordinate and an average concentration. This series of records is printed for each averaging time requested. The model allows printer and plotter output for 1-hour averages, 3-hour averages, 8-hour averages, 24-hour averages and a long-term average which is the average over the entire meteorological data base provided. Additionally, a sequential output "tape" file for post-processing with the POSTZ program can be created. Up to 1200 receptors can be processed, and up to 121 sources can be processed. It should be noted that while FDM has the capability of treating 1200 receptors, POSTZ can only accept 200 receptors, thus long-term sequential uses of FDM should carefully consider the number of receptors to be used.

The sources can be of three types: points, lines or areas. The line source and area source algorithms are based on algorithms in the CALINE3 Model (California Department of Transportation, 1979).

For area sources, the user supplies the coordinates of the center and the dimension in the x and y directions. Area sources need not be square, but rather can be rectangular, up to an aspect ratio of 1 to 5 (ratio of width to length). Area sources with the length greater than five times the width must be divided in a series of area sources, or modeled as a line source. The model divides the area source into a series of line sources perpendicular to the wind direction. Emissions from all sources may be divided into a maximum of 20 particle size classes.

2.0 TECHNICAL DESCRIPTION

Basic Equations

The Fugitive Dust Model (FDM) is an analytical air quality model specifically designed for the analysis of the dispersion of fugitive dust. The model incorporates a detailed deposition routine based on the equations of Ermak (1977). The basic equations as developed by Ermak are described in the remainder of this section. The general equation governing pollutant transport and dispersion in the atmosphere, when the pollutant is composed of uniformly-sized particles is as follows:

$$\frac{\partial \chi}{\partial t} = \frac{\partial}{\partial x} K_x \frac{\partial \chi}{\partial x} - u \frac{\partial \chi}{\partial x} + \frac{\partial}{\partial y} K_y \frac{\partial \chi}{\partial y} + \frac{\partial}{\partial z} K_z \frac{\partial \chi}{\partial z} + v_g \frac{\partial \chi}{\partial z} \qquad (1)$$

where:
χ = concentration (g/m^3)
K_x, K_y, K_z = eddy diffusivity in the x, y and z directions (m^2/sec)
t = time (sec)
x, y, z = coordinates in three dimension space where x is parallel with the wind direction, y is perpendicular to x and parallel with the surface and z is perpendicular to both x and the surface (m)
u = wind speed (m/sec)
v_g = gravitational settling velocity (m/sec) where positive is in the downward direction

To solve equation (1), several simplifying assumptions are made. First, the diffusion in the x direction is assumed to be small compared with the advection by the wind speed in that direction. This assumption eliminates the need consider any cases other than steady state. Second, the eddy diffusivities are assumed to be functions only of downwind distance (as will later be seen, further constraints are placed on the eddy diffusivity to obtain the gradient-transfer solution). The resulting diffusion equation is greatly simplified from equation (1):

$$u\frac{\partial\chi}{\partial x} = K_y\frac{\partial^2\chi}{\partial y^2} + K_z\frac{\partial^2\chi}{\partial z^2} + v_g\frac{\partial\chi}{\partial z} \qquad (2)$$

A further assumption regarding the eddy diffusivity is made which generally means that the eddy diffusivity must be constant for all space and time. Actually, to obtain the solution, it is only necessary that the eddy diffusivity have the same functional dependance on the downwind distance as v_g. Since v_g is generally a constant, the eddy diffusivity in all directions is also assumed to be represented by a single parameter denoted by K. The relationship between K and the more commonly-seen diffusion parameter, the standard deviation of the concentration in the y and z directions, σ_y and σ_z, is as follows:

$$\sigma^2(x) = \frac{2}{u}\int_0^x K dx \qquad (3)$$

since K is to be assumed constant with x, it is obvious that the solution to be obtained is only strictly valid for cases where the σ varies as function of downwind distance to the 0.5 power. The equation thus obtained is:

$$\chi = \frac{Q}{2\pi\sigma_y\sigma_z u} e^{-\frac{y^2}{2\sigma_y^2}} e^{\left[\frac{-v_g(z-h)}{2K} - \frac{v_g^2\sigma_z^2}{8K^2}\right]} \left[e^{\frac{-(z-h)^2}{2\sigma_z^2}} + e^{\frac{-(z+h)^2}{2\sigma_z^2}} - \sqrt{2\pi}\frac{V_1\sigma_z}{K} e^{\left[\frac{v_1(z+h)}{K} + \frac{v_1^2\sigma_z^2}{2K^2}\right]} erfc\left[\frac{V_1\sigma_z}{\sqrt{2}K} + \frac{z+h}{\sqrt{2}\sigma_z}\right]\right] \qquad (4)$$

where:
χ = concentration in g/m^3
Q = Emission rate (g/sec)
u = wind speed (m/sec)
σ_y, σ_z = standard deviation of concentration in the y and z directions (m)
x,y,z = coordinates of the receptor (m)
v_g = gravitational settling velocity (m/sec)
h = plume centerline height (m)
K = eddy diffusivity (m^2/sec)
v_1 = $u_d - v_g/2$

u_d = deposition velocity (m/sec). A basic assumption in the solution of this equation is that deposition will be proportional to concentration at the surface. The deposition velocity is the proportionality constant (see equation (9) below).

[Note: Ermak's original paper contained some typographical errors in the equation which have been corrected here]

With the assumption that K is constant, and the assumption from equation (3) above, we can assume:

$$K = \frac{\sigma_z^2 u}{2x} \qquad (5)$$

The following two substitutions are made for convenience:

$$\gamma = \frac{v_1\sqrt{2}x}{\sigma_z u} + \frac{z+h}{\sqrt{2}\sigma_z} \qquad (6)$$

$$\beta = \frac{x}{\sqrt{2}\sigma_z u} \qquad (7)$$

With these substitutions, equation (4) can be written in the form:

$$\chi = \frac{Q}{2\pi\sigma_y\sigma_z u} e^{\left[-\frac{v_2(z-h)\sqrt{2}\beta}{\sigma_z} - v_2^2\beta^2\right]} \left[e^{\left[-\frac{(z-h)^2}{2\sigma_z^2}\right]} + e^{\left[-\frac{(z+h)^2}{2\sigma_z^2}\right]} - 4\sqrt{\pi}\, v_1 \beta e^{\left[-\frac{(z+h)^2}{2\sigma_z^2}\right]} e^{\gamma^2} \mathrm{erfc}(\gamma) \right] \qquad (8)$$

The assumption regarding the behavior of K with respect to x leads to some inconsistencies when equation (4) is used with the standard Turner σ_y and σ_z curves. The inconsistency presents itself as a failure to conserve mass as the plume travels downwind. A numerical integration technique was used to calculate a correction term for modifying the concentration predictions of equation (4) to ensure that conservation of mass is obtained. The details of the development of the mass conservation correction factors are presented in the remainder of this section.

The basic equation which defines the deposition algorithm is that:

$$D = u_d\chi|_{z=0} \tag{9}$$

where:
D = Deposition rate
u_d = Deposition velocity
χ = Concentration (from equation 8)

We can define corrected concentrations as the concentrations above, multiplied by some function of x, which we will call here q(x):

$$C = \chi q(x) \tag{10}$$

$$D = u_d q(x)\, C|_{z=0} \tag{11}$$

The requirement for mass conservation can be written as follows:

$$\int_0^x \int_{-\infty}^{\infty} D\,dy\,dx + u \int_0^{\infty} \int_{-\infty}^{\infty} C\,dy\,dz = Q \tag{12}$$

Substituting, we obtain the following form of the above equation:

$$\int_0^x u_d q(x)\, C_{cwi}|_{z=0}\,dx + u q(x) \int_0^{\infty} C_{cwi}\,dz = Q \tag{13}$$

where:

$$C_{cwi} = \int_{-\infty}^{\infty} C dy \qquad (14)$$

Differentiating both sides of the equation by x we obtain:

$$u_d q(x)\, C_{cwi} + u \frac{\partial}{\partial x}\left[q(x) \int_0^{\infty} C_{cwi} dz \right] = 0 \qquad (15)$$

Reforming, we obtain a first-order differential equation in x:

$$\frac{\partial q(x)}{\partial x} u \int_0^{\infty} C_{cwi} dz + q(x)\left[u_d C_{cwi}\big|_{z=0} + u \frac{\partial}{\partial x}\left(\int_0^{\infty} C_{cwi} dz \right)\right] = 0 \qquad (16)$$

The above equation was solved using a third-order Runge-Kutta integration process as follows:

$$Let \quad A(x) = \int_0^{\infty} C_{cwi} dz \qquad (17)$$

Then:

$$\frac{\partial q(x)}{\partial x} uA(x) + q(x)\left[u_d C_{cwi}\big|_{z=0} + u \frac{\partial A(x)}{\partial x} \right] = 0 \qquad (18)$$

$$\frac{\partial q(x)}{\partial x} = \frac{-q(x)\left[u_d C_{cwi}\big|_{z=0} + u \frac{\partial A(x)}{\partial x} \right]}{uA(x)} \qquad (19)$$

$$dq(x) = \frac{-q(x)\left[u_d C_{cwi}\big|_{z=0} + u \frac{\partial A(x)}{\partial x} \right]}{uA(x)} dx \qquad (20)$$

$$k_1 = \frac{-q|_{x=x_i}\left[u_d C_{cwi}|_{x=x_i,\,z=0} + u\dfrac{A|_{x=x_i+\frac{dx}{2}} - A|_{x=x_i-\frac{dx}{2}}}{dx}\right]}{uA|_{x=x_i}}dx \tag{21}$$

$$k_2 = \frac{-\left(q|_{x=x_i}+\dfrac{k_1}{2}\right)\left[u_d C_{cwi}|_{x=x_i+\frac{dx}{2},\,z=0} + u\dfrac{A|_{x=x_i+dx} - A|_{x=x_i}}{dx}\right]}{uA|_{x=x_i+\frac{dx}{2}}}dx \tag{22}$$

$$k_3 = \frac{-(q|_{x=x_i}+2k_2-k_1)\left[u_d C_{cwi}|_{x=x_i+dx,\,z=0} + u\dfrac{A|_{x=x_i+1.5dx} - A|_{x=x_i+\frac{dx}{2}}}{dx}\right]}{uA|_{x=x_i+dx}}dx \tag{23}$$

$$q_{x=x_i+dx} = q_{x=x_i} + \frac{1}{6}(k_1 + 4k_2 + k_3) \tag{24}$$

A variable step length (dx) was used for using the above numerical integration scheme to determine q(x). A total of 100 steps from 1 meter to 50,000 meters was used in the numerical integration. From these 100 values of downwind distance and q(x), a least squares fit was performed for an equation of the form:

$$\log(q(x)) = b_0 + b_1\log(x) + b_2(\log(x))^2 + b_3(\log(x))^3 + b_4(\log(x))^4 \tag{25}$$

Separate values of $b_0..b_4$ were calculated for the combination of 6 different wind speeds, 6 different stability classes, 6 different particle size classes and 5 different release heights. Over 1000 values of $b_0..b_4$ were computed and entered into the FDM code.

Treatment of Meteorological Conditions

Meteorological data can be provided to the FDM in three formats: a sequentially processed meteorological data set using the format produced by the RAMMET pre-processor, card images of hourly meteorological data or a statistically-produced STability ARray (STAR). If sequential meteorological data are used (either the RAMMET pre-processed format or card image format), the model requires average values over the shortest averaging period for wind speed, wind direction, atmospheric stability, temperature and mixing height. Wind speed is used directly in the above equation to determine the concentration. Wind speed is also used in combination with temperature and atmospheric stability to determine the values for deposition velocity if the user asks the model to compute deposition velocity (the user can alternatively enter deposition velocities with the input stream). Wind direction is used to determine the location of the receptor with respect to the center point of each source in a coordinate system defined with the wind direction parallel to the x-axis. Wind directions are entered as the number of degrees clockwise from north that the wind is coming from. This point is significant, since some air quality models (e.g. the Industrial Source Complex Model) require wind direction to be entered as the direction towards which the wind is moving.

Atmospheric stability is used to determine the values for the standard deviations of the horizontal and vertical plume dimension above. The atmospheric stability for each unit of meteorological data (usually hourly values) is specified as one of six possible stability classes, using the classification scheme of Turner (1970). The computation of the actual parameters from the Turner classification is made using the equations and coefficients listed in the User's Guide for the Industrial Source Complex (ISC) Model (EPA, 1986). The determination of the values for these parameters is based solely on downwind distance and stability class.

The model is generally very insensitive to values of the mixing height, since fugitive dust emissions are usually released at ground level and reflections off the mixing height are only significant at very far distances from the source or at elevated receptors. However, the model does consider such reflections in the standard fashion. Equation (8) is computed at $z = z+nH_m$ and $z = z-nH_m$ for even values of n starting with 2 and progressing until concentrations are no longer significant. The values computed from these reflections are added to the value computed from the original computation of Equation (8) to arrive at the total concentration at the receptor height. Some users have noted very slow computation times when very low mixing heights are input. Users are urged to consider the computation time when selecting mixing heights for input to the model.

It should also be noted that when the RAMMET preprocessor is used for preparing a sequential meteorological data set, often very low values of the mixing height can be computed. When using such a data set, the user is encouraged to examine the meteorological conditions for the highest days to determine that meteorological conditions are realistic. FDM has been configured to automatically set the mixing height for stable conditions to 5000. meters and to limit the mixing height for other stability conditions to no less than 100. meters. Since long-term meteorological data sets often include some missing data, the model has been designed to recognize missing or bad data using coding involving series of 9's. Bad or missing wind speeds are coded as 999.9 meters per second or larger, missing wind directions are coded as 999.9 degrees clockwise from north, and missing or bad stabilities are coded as 9.

Missing data includes calm conditions which are defined as wind speeds less than 1.0 meter per second. Missing data are treated by the model according to the EPA "calms policy" (Guideline on Air Quality Models, Section 9.3.4.2). The calms policy is based on the assumption that wind speeds less than 1.0 meters per second are not well simulated by Gaussian Plume Models. FDM has been designed to eliminate hours with wind speeds less than 1.0 meters per second from the analysis and the averaging computations. For the purposes of calculating averages, if a small amount of data is missing, the model computes the average on the basis of the data which remain. For example, if 24-hour averages are being computed, and 2 hours within a 24-hour period are missing, the model computes the 24-hour average as a 22-hour average of the remaining good hours. If however, the number of missing, bad or calm hours exceed a threshold value defined separately for each hour, the model computes the average as if there were at least the threshold number of hours, and that the missing hours produced a zero concentration and deposition rate. For example, for 24-hour averages, the threshold is 18 good hours. Thus if 8 hours of data were missing from a 24-hour period, the model would compute the 24-hour average concentration by adding the concentrations for the 16 good hours and dividing the total by 18. Thresholds for the averaging times considered by FDM are:

Averaging time	Threshold
1-hour	1
3-hour	3
8-hour	6
24-hour	18

For long-term averages, such as the annual average of an entire year of data, the model computes the average as an average of the good hours of data without a threshold.

One important aspect of the calms policy that is not treated in FDM is the proper proceedure to processing low wind speed hours prior to entering them in a computer model. If the threshold of the meteorological sensor which collected the data is less than 1.0 meter per second, the calms policy calls for the user to determine if each hour of meteorological data is greater then the threshold of the sensor, but less than 1.0 meter per second. In that event, the user is instructed to increase the wind speed for that hour to 1.0 meter per second so that FDM will keep the hour in the computations.

Treatment of Deposition

Equation (8) accounts for deposition through two parameters: the gravitational settling velocity and the deposition velocity. As its name implies, the gravitational settling velocity accounts for removal of particulate matter from the atmosphere due to gravity. Since only the larger particles have sufficient mass to overcome turbulent eddies, this mechanism is significant only for the larger size ranges (e.g. particles greater than 30 micrometers). The deposition velocity accounts for removal of particles by all methods, including turbulent motion which brings the particulate matter into contact with the surface and

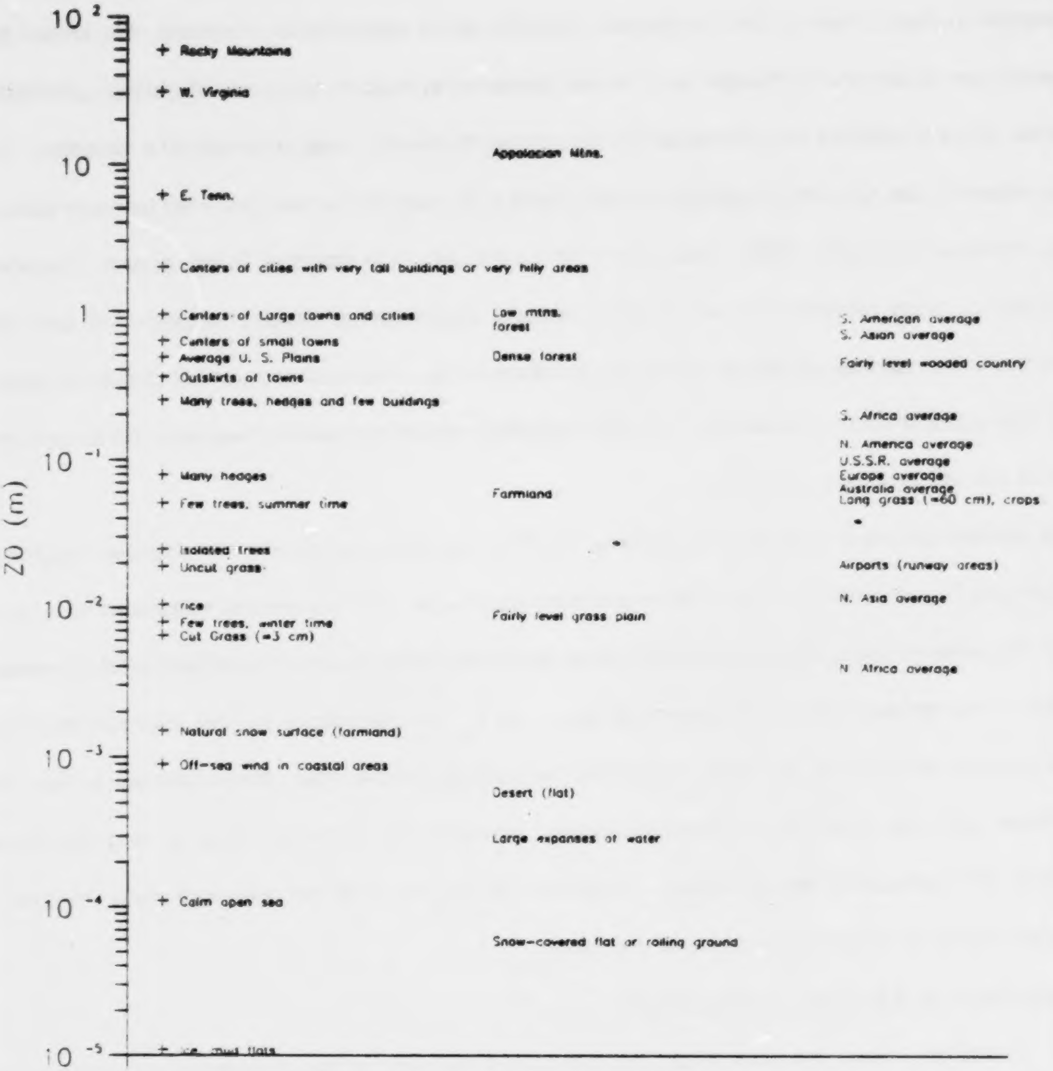
15

allows it to be removed by impaction or adsorption at the surface. It is known that for smaller particles the deposition velocity is significantly different from the gravitational settling velocity, while for large particles they are roughly the same (Nifong and Winchester 1970). In the FDM the emission rate, Q, is divided into a user determined number of particles size classes (maximum of 20). Each of the classes has a unique gravitational settling velocity and deposition velocity. The user may enter these parameters directly, or may enter characteristic diameters for each particle size class and ask the model to compute the deposition velocity and gravitational settling velocity. The method used by the model to compute the gravitational settling velocities and deposition velocities is modeled after the work of Sehmel and Hodgson (1978). The portion of the FDM computer program which calculates the gravitational settling velocity and deposition velocity was written by Mr. Bart Croes at the California Air Resource Board (CARB) (Croes, 1987).

Key inputs to the method used by Sehmel and Croes are the roughness height and the friction velocity. Friction velocities are calculated internally in the FDM from the wind speed and the reference height of the meteorological data. The computer program for the computation of the friction velocity was written by Gregory J. McRae (1977) and provided by Mr. Croes of the CARB. The roughness height is an input parameter of the model. Figure 1 provides some typical values for the roughness height.

Each particle size class is treated separately by the model. The results for different particle size classes are summed at the end to develop a total suspended particulate concentration. Alternatively, the model can compute the deposition rate. In this event, the concentrations for each particle size class are multiplied by the deposition velocity for that particle size class and the results are summed to determine the total deposition rate.

As noted earlier, a major difference between FDM and other available air quality models is the ability to treat both turbulent and gravitational removal mechanisms for particles. In doing so, the gradient-transfer deposition algorithm is used. The gradient transfer algorithm is also termed "K-theory", because turbulent transfer processes are assumed to be proportional to the gradient or first derivative of concentration. The proportionality constant is called the "eddy diffusivity", and is customarily denoted by



Based on Stull (1988)

Figure 1. Typical Values for the Roughness height

the symbol "K".

A critical assumption necessary to obtain the solution shown in equation (8) is that the eddy diffusivity be constant for all space (isotropic eddy diffusivity). Although isotropic turbulence is a common assumption in many areas of fluid mechanics, including some atmospheric processes, it is known that a plume's rate of dispersion changes as it moves downwind in most atmospheric dispersion processes, because eddys of different sizes dominate the dispersion at different times in the plume's evolution. This fact is evident in the standard dispersion curves (sigma-y and sigma-z curves) provided by many authors and summarized by Turner (1970). Since the FDM makes use of the standard Turner curves, a potential inconsistency exists between the use of the constant-K assumption to develop equation (4), and then allowing K to be represented by the standard deviations in the crosswind and vertical directions (sigma y and sigma z) in the standard fashion. The inconsistency results in a failure of equation (8) to conserve mass as the plume travels downwind.

To alleviate the mass conservation problem, the FDM has been corrected in the manner suggested by Horst and Doran (1986). Concentration and deposition have been numerically integrated for a large number of cases involving different meteorological conditions, different particle sizes and different release heights. A numerical solution was developed to correct the concentrations so that approximate mass conservation is obtained for all cases. In general, for particles smaller than 10 micrometers or less, the corrections are very small, for all cases examined. However, for larger particles, at long downwind distances, the corrections are significant. Correction factors are built into the model and the use of correction factors is entirely transparent to the user.

Emission Rates as a Function of Wind Speed

One of the unique characteristics of fugitive dust is that often emission rates are a function of the wind speed. The FDM has the capability to directly compute the effect of wind speed on emission rate. For each source, the emission rate is calculated by the equation:

$$Q = Q_0 u^w \tag{26}$$

where: Q = emission rate in g/sec
Q_0 = proportionality constant
u = wind speed (m/sec)
s = wind speed dependance parameter

The emissions for every source are entered as a proportionality constant and a wind speed dependance parameter (Q_0 and s). For sources which do not vary with wind speed, the emission rate is simply entered for Q_0 and s is entered as 0 (the default). However, for sources which do vary with wind speed both parameters must be specified. Examples would include the cubic dependance on wind speed of some wind erosion emission estimates (Woodruff and Siddoway, 1965). Also in "Compilation of Air Pollutant Emission Factors" (EPA, 1985), many fugitive dust sources are shown to linearly depend on wind speed, such as batch and continuous loading and unloading operations and losses from open storage stockpiles.

Treatment for Line Sources

Line sources are treated virtually the same as the CALINE3 Model (California Department of Transportation, 1979). The code has actually been lifted from the CALINE3 Model and incorporated in the FDM for the line source treatment. The CALINE3 line source algorithm involves the division of the line source into a series of elements. The spacing of the division between elements is determined by the angle of the line source with respect to the wind direction and the receptor. A line is defined which passes through the receptor and is parallel to the wind. The area of the line source near this parallel line is divided into many elements, which are roughly square in shape. Portions of the line source further from the parallel line are divided into fewer elements which are longer (more rectangular). The number of elements and their orientation depends on the geometry of the line source with respect to the receptor and the wind.

Each element is further divided into sub-elements. These sub-elements are represented in the model as small finite line sources which are perpendicular to the wind direction. These sub-elements are represented in the concentration equations by a cross-wind integrated version of equation (8). The finite integral of the equation is computed using a numerical approximation for the error function. Further details on the algorithm for line sources can be found in Appendix C, taken from the CALINE3 User's Guide referenced above. The deposition capability has been modified to be consistent with the treatment above.

Treatment for Area Sources

Area sources are specified by the user with a center point, an x-dimension, a y-dimension, a rotation angle and the various emission parameters from the above equations. The model computes concentrations from the area sources by first rotating the coordinate system so that the origin is at the receptor and the x-axis is aligned with the wind direction. Figure 2 illustrates the orientation of the receptor and a typical area source. The portion of the area source which is upwind (in the range of positive x values) is considered. The area source is divided into a series of line sources oriented perpendicular to the wind direction.

There are two major options for the area source algorithm: a default 5-line integration, or a convergent integration. In the default 5-line version, the model divides the area source into 5 lines perpendicular to the wind direction. In the convergent version, the model begins by dividing the area into 5 lines. It computes a concentration at each receptor for the 5-line integration, then repeats the process for using a 6-line integration. If the results are less than 1% different at all receptors, the model uses the 6-line integration. If, however, one or more receptors fails the 1% test, the model computes a 10 line integration and an 11-line integration and makes the same comparison. It continues with further sub-divisions in increments of 5 (15/16, 20/21, 25/26, etc.) until convergence is obtained. The maximum allowable number of lines in the integration is 901. If convergence has not been obtained with 901 lines in the integration, the model uses the 901-line integration. Since the line sources are perpendicular to the wind direction, it is possible to use a finite integration to solve the line source integral for these lines. As with the line source sub-elements, the cross-wind integrated form of the dispersion equation is used, with a numerical routine used for determining the error function. It is possible for receptors to be located within area sources, but only the portion of the area source upwind of the receptor is considered.

It should be noted that the convergent area source algorithm may require substantial additional computation time. Run times have been observed to increase by an order of magnitude in some cases using the convergent algorithm. The user should use discretion when selecting this algorithm, particularly for cases involving long meteorological data bases.

The rotation angle supplied for area sources by the user requires further explanation. The geometry of the area source is defined by the user by the specification of five parameters. The x and y coordinates of the center point of the area source are straight-forward. Usually, the user is working with a map which defines an area he or she wishes to model. The area may be irregular in shape and oriented in any fashion. Typically, the user would draw a rectangle on the map to simulate part or all of the area to be modeled. The rectangle can be oriented in any way. By drawing lines to connect opposite corners of the rectangle, the center point is determined and the coordinates determined. The second two parameters are the x and y dimensions of the area source. Typically,the area source will not be located with the sides parallel to the x and y axis of the map. The user selects one of the sides to represent the x-side (it doesn't matter which). The length of the selected side is entered as the x dimension, and the other side dimension is entered as the y dimension. Finally, the user determines the angle of the side selected as the x-axis with respect to the true x-axis. This angle is the area source rotation angle and is the final parameter entered for each source. It is important to note that the angle must be in the range of -90 degrees to plus 90 degrees. Values larger than 90 degrees will not be accepted by the model.

The model determines the line sources used in the integration of the area source by rotating the coordinate system so that the x-axis is parallel to the wind direction. In this rotated coordinate system, the first step is to determine the x-extent of the area source. The x-extent is found by determining the x and y coordinates of the four corners of the area source in the rotated system, and simply subtracting the smallest x value from the largest x value. The actual line sources used in the integration will be perpendicular to the wind, and hence parallel to the y axis in the rotated coordinate system. The x extent is divided by the number of steps in the integration, and the x coordinate for each of the line sources is determined as the center of each step. Finally, the y coordinates of the line sources are determined by computing equations for four lines which are colinear with the sides of the area source. Each line source

21

will intersect the four lines of the area source sides at four distinct points (special cases are made when the sides of the area source are parallel to the x and y axes). Since the line sources are parallel to the y axis, the four intersection points will all have the same x value, but different y values. The y values can be sorted and the middle two values will define a line perpendicular to the wind and within the area source.

Special Considerations when Using a STAR

If meteorological data is provided to the model in the form of a Stability Array, the model computes concentrations in a fundamentally different manner from the other meteorological options. Instead of using the CALINE3 algorithm as the basis for line and area sources, the model now computes concentrations as 22.5 degree sector averages, and much of the CALINE3 algorithm is moot. The sector averaging differences are true for point sources as well. In fact the model calls entirely different subroutines for computations with a STAR. The option of writing a sequential output file for post-processing is also eliminated when running with a STAR. The same deposition algorithms are used. The main difference is that Equation (8) is integrated in the cross wind (y) direction from minus infinity to plus infinity and the result divided evenly over a the 22.5 degree sector referenced by one of the 16 possible wind direction categories in the STAR.

To eliminate large differences between adjacent receptors across sector boundaries, the model smooths concentrations between adjacent sectors. The method of using the smoothing function is to consider a receptor's placement within a sector. For example, for a point source each receptor will be contained within only one downwind sector. The frequency used in the concentration computation for that receptor, however, is a weighted average of the frequency of the sector the receptor is in and the nearest other sector. The weighting is determined by how far the receptor is from the sector center. If it lies directly on the sector center, then the frequency used is exactly that of the sector it lies in. If the receptor lies on the boundary of two sectors, the frequency used is the average of the frequency of the two sectors. For points in between these two extremes, a linear interpolation is used.

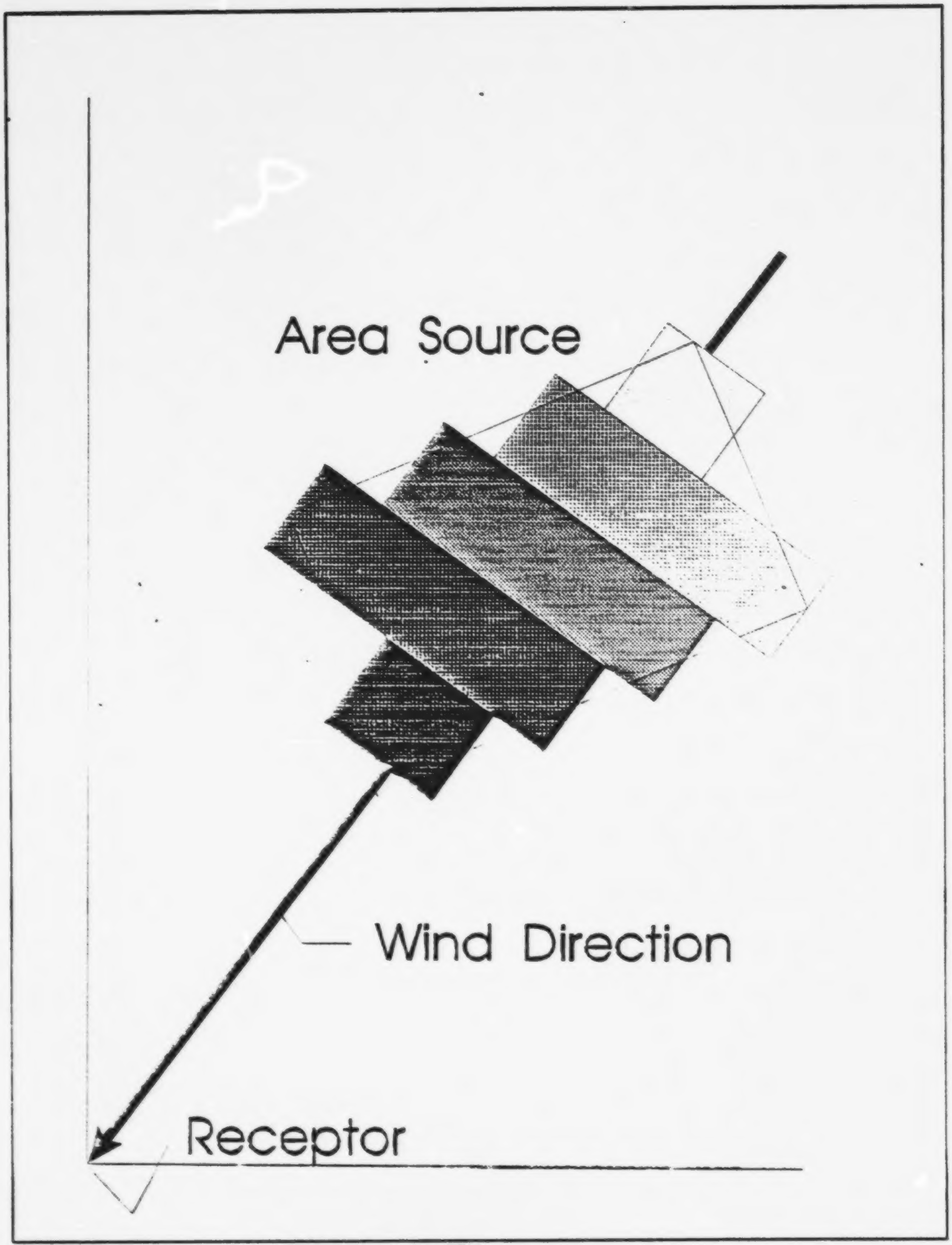

Area Source
Wind Direction
Receptor

Figure 2 Area Source Treatment in FDM

3.0 USER'S INSTRUCTIONS

Information is provided to the model in either one or two files. The first is referred to as the FDM input file and contains information on the receptors, sources and various model switches and options. The FDM input file also can contain the meteorological data, expressed as a series of card-images (either as a series of 1-hour episodes, or a statistically produced STability ARray (STAR)). If, however, the user elects to supply meteorological data in the standard pre-processed format, using the RAMMET pre-processor program, a second file must be identified with the meteorological data.

The model was developed on an IBM-PC compatible computer, but is written in standard FORTRAN code, and may be adapted for operation on a mainframe or other computer system. The instructions provided here are those which apply to an IBM-PC compatible computer, running a standard Disk Operating System (DOS). The model requirements for PC operation are a minimum of 500 K of memory and a math-coprocessor chip (e.g. 80287, etc). An additional requirement is that the device driver, ANSI.SYS or a compatible be installed on the machine. The ANSI.SYS file is provided with most DOS packages. To install it, the user must make sure that the statement "DEVICE = ANSI.SYS" is present in the CONFIG.SYS file in the user's root directory of the drive used to boot the computer. It should be noted that some operating systems provide their own special version of the ANSI.SYS device driver. For example the commercial software called DOUBLEDOS provides a version called "DBLDANSI.SYS". The FDM package is compatible with any such device driver.

The version of the model supplied on the distribution diskette was compiled using the Lahey F77L FORTRAN compiler. As such, it uses two special routines provided with the Lahey compiler, which must be deleted, or replaced if the user decides to compile the program with a different compiler. First, the model uses a command-line interface routine called GETCL. The interface allows the user to name the input file on the command line which begins the execution of the program. The command line interface allows the user to "batch" run a large number of runs by simply creating a batch file with a series of command lines.

The second Lahey routine called by the program is the UNDERZERO call which prevents underflows (very small numbers). Some compilers simply treat very large negative exponents on numbers as zero. The Lahey compiler requires calling this subroutine to make numbers with large negative exponents default to zero. The user should consult the manual for the compiler the user intends to use for information on the treatment of underflows.

If the user does not specify a filename on the command line, the program prompts the user for the names of the input files and output files. The input files must have been prepared prior to the operation of the run. Directions for preparing the FDM input file are detailed in the next section of this chapter. If the meteorological option is selected to provide the data in pre-processed format, it must be in a standard "UNFORMATTED" file. Compilers differ in the form for "UNFORMATTED" files, thus it may be necessary to run a separate program, also provided in this package, called "UNFORMAT" which will take a formatted file containing the RAMMET pre-processed output and transform it to an unformatted file, suitable for the FDM input. Contained in the diskettes which are provided is a FORTRAN program for transforming the data if required, along with a test data set illustrating the use of this program.

Further information on the files needed and produced by FDM are provided below. For here it is important only to know that there are two possible input files (one required and one optional) and three possible output files (printer, plotter and sequential concentration for post processing). Once the input files are prepared and stored on a disk drive, the FDM program is initiated by typing "FDM90121" followed by a file name. Note that the name of the program includes the version number to prevent confusion with previous or later versions of the program. The three letters FDM are always at the start of the program name. The next two characters are the year of the current version, and the final 3 characters are the Julian day (numbered day of the year from 1 to 365 or 366) of the current version. If later versions of the model are issued they too will be executed by typing a program name of this form. Card input files are always designated with the .IN extension, and printed output files are always use the .OUT extension. Sequential meteorological data sets are designated by the .MET extension. Plotter output files use the

.DAT extension, while a sequential output for post processing uses the .CON extension. For example, if a run was being made with the card input stored in a file called RUN1.IN, and a sequential meteorological data set was stored in RUN1.MET, the program would be started by issuing the command from the DOS prompt:

```
FDM90121 RUN1
```

The program will automatically write printed output to a file called RUN1.OUT, plotter output to a file called RUN1.DAT (if selected), and sequential concentration output for postprocessing to a file called RUN1.CON (if selected). If the user fails to enter a file name after the FDM90121 command, the program prompts for the name of the input files, and prompts for file names where the various output files are to go.

> **CAUTION** – The FDM program will erase old files with the same name as that specified for output, so that if the user enters a name for the output file which already exists on the disk drive, it will be overwritten.

3.1 The FDM Input File

The FDM input file provides the model with most, if not all, of the information needed for execution of the program. Information is provided to the model through a series of card images which consist of a maximum of 80 columns of data (i.e., 80 characters per line). Table 1 provides a summary of the information needed and the format for each entry in the file. The input file contains three general types of information:

- general values and model switches and options
- receptor locations – the locations at which concentrations and depositions are to be calculated,
- source data, including the geometric information on source locations, sizes and orientations, the emission information and the release heights, and

- meteorological data, if not provided by a separate sequential file.

The first group of data includes a run title, for documentation purposes only, the selection of area source algorithm to use: convergent or default (see Chapter 2 for a more detailed discussion of these two options), the selection of format for the meteorological data, the selection of which output files to create, and what items are to be contained in each output file. A specific discussion of the output options is presented below. The general information section also includes the specification of the number of receptors and sources to include, the number of particle size categories to use, a characteristic particle diameter for each particle size category, a mass fraction for each particle size category, a density of the particulate matter, and a roughness height for the site (see Chapter 2 for more guidance and information on the selection of roughness height).

Sample input files and output files are included on the diskette. The meaning and possible values for each of the parameters is explained in Table 1.

The other possible input file is a RAMMET pre-processed meteorological data set. The model requires this information to be provided in an "UNFORMATTED" file, which is discussed above. The program UNFORMAT is provided on the diskette for converting formatted pre-processed meteorological data into unformatted format.

3.2 The FDM output files

Output can be obtained from FDM in three formats. First, the standard output file, as contained on the diskette, which documents all the inputs and the computed concentrations or depositions for the model. The information to be provided in the output file is selected by the user in the input file. The options include which averaging times to consider for the meteorological data provided. Unless directed by the user differently, the model assumes each meteorological entry represents an hourly average of the meteorological conditions. The model calculates concentration and deposition values for each of these entered conditions. The user may report every value calculated, or he may choose to report only averages of groups of these values. For example, if meteorological data comprising 48-hours of hourly-averaged meteorological data are entered by the user, the model will compute 48 1-hour average concentrations and depositions. However, the user may not wish to have all these data reported, thus the user can direct the model to report only two 24-hour averages, six 8-hour averages, sixteen 3-hour averages, one 48-hour average, all 48 one-hour averages, or any combination of the above values.

Further, for longer-term data processing, the model can be directed to sort the values computed for each of the averaging periods and report only the top values. These top values are reported in two formats: a top 50 table, which consists of the top 50 averages computed in the run, regardless of receptor location, and a high two table, which consists of a table showing the two highest averages computed at each receptor. For example, if the user directs the model to analyze a full year of meteorological data (8760 or 8784 hours) and compute 24-hour averages at 10 receptors, a total of 3650 (or 3660) 24-hour average concentrations and depositions will be computed. With the top value output selected, the model will sort the concentration values to find the top 50 24-hour averages computed at any receptor location and the top two values at each receptor location. Note that the corresponding deposition rate is reported which generally is co-located with the peak concentration value, but no actual sorting is performed of the deposition values.

The second form of output is a "plotter" file which contains concentrations for each averaging time selected by the user along with the coordinates for those concentrations. The format is a generic form which simply presents the x coordinate, the y coordinate, the concentration and the deposition rate. It should be noted that this format is ideal for input to gridding and plotting programs such as the Golden Graphics Surfer program which can produce isopleth plots of concentration. However, the user is cautioned that the information reported in plotter file is determined by the selections for the printed output. If the user selects only to print top values in the printed file, the plotter file, although created by the program, will be empty. To obtain a plotter file, the user must actually specify that every average be printed for a particular averaging time.

The third format for the output is a sequential file of concentrations for post processing by the POSTZ program, available on the SCRAM. POSTZ is a post-processor designed for the SHORTZ air quality model. The SHORTZ air quality model has the capability of writing an output file of sequential concentrations for every combination of meteorological condition, source and receptor. These tapes, on the IBM PC system take the form of a disk file. The FDM has been equipped with the option of writing a tape of a format suitable for input to the POSTZ program. Much of the information on the tape is not used by the POSTZ model, thus in many cases the FDM has been instructed to write "dummy" variables to the tape to keep the format correct, but which do not enter in the calculation of any of the POSTZ results.

The advantage to the POSTZ post-processor option is that many alternate averaging times can be examined, specific periods of a longer meteorological data base can be examined, the results for certain sources can be scaled up or down, and a number of other manipulations can be performed with the data. The POSTZ program also prepares high-five and top 50 tables which are useful for many regulatory applications of the model.

The major disadvantages to using the POSTZ program are that the sequential tape file written by FDM for POSTZ input can be very large, and can exceed the capacity of many typical PC hard disks. For example, a run containing 15 sources, 200 receptors and 1 year of sequential meteorological data will write a tape file that is over 100,000,000 bytes in length. Discretion must be exercised when selecting this option. It is also important to note that the post-processing option is only available for concentration.

TABLE 1
SUMMARY OF INFORMATION REQUIRED FOR FDM INPUT

Card 1 Title Card

Col	Format	Information
1-80	A80	Title

Card 2 Switches

Col	Format	Information
2	I1	Area source algorithm switch. Two options are available for area sources, the default 5-line integration is selected by entering a value of 1 for this parameter. The alternate convergent algorithm may be selected by entering a value of 2 here. The user is cautioned that the convergent algorithm can be very slow in execution time and can drastically increase run times. Default is 1.
4	I1	Meteorological Data Option Switch. If = 1 then met. data is read from cards (format shown below) contained later in this input file. If = 2 then met. data is read from pre-processed meteorological file. If = 3 then met. data is read as a STAR contained later in this input file (format 6F10.0). Note that the selection of the STAR option makes many of the later options not applicable. Default is 1.
6	I1	Plotter Output Switch. If = 1 then no plotter file is made. If = 2 then a plotter file name is asked for and the model writes a file with a formatted output of x, y, concentation, deposition for every averaging time selected with a value of 2 or 4 in columns 14, 16, 18, 20 or 22. Note that a value of 3 in any of these columns will not produce a plotter output. Default is 1.

8	**I1**	**Print Output Switch. If = 1 then meteorological data are not printed. If = 2 then meteorological data are printed. Default is 1.**
10	**I1**	**Post Processor Switch. If = 1 then no post processor file is written. If = 2, then a post processor file is written which can be processed with the POSTZ program to develop High-5 tables, scale sources, or other operations. Note that the maximum number of receptors possible for the post processor is 200.** The user should see the POSTZ User's Guide for further information. Note that post processing is performed only for concentration -- no post processing option is available for deposition. This option is not available and this switch is ignored when the met. option switch = 3. Default is 1.
12	I1	Deposition Parameters Option Switch. If = 1 then the model will compute deposition velocity and gravitational settling velocity automatically on an hour by hour basis. If = 2 then the User will enter single values of the deposition velocity and gravitational velocity for each particle size class to be used for all hours. Default is 1.
14	I1	1-Hour Output Switch. If = 1 then 1-hour average concentrations are not printed, If = 2 then 1-hour average concentrations are printed. If = 3, a top 50 and high 2 table are prepared for this averaging time. If = 4, both the top 50, high 2 and every 1-hour average concentration are printed. This option is not available and this switch is ignored when the met. option switch = 3. Default is 1.
16	I1	3-Hour Output Switch. If = 1 then 3-hour average concentrations are

		not printed. If = 2 then 3-hour average concentrations are printed. If = 3, a top 50 and high 2 table are prepared for this averaging time. If = 4, both the top 50, high 2 and every 3-hour average concentration are printed. This option is not available and this switch is ignored when the met. option switch = 3. Default is 1.
18	I1	8-Hour Output Switch. If = 1 then 8-hour average concentrations are not printed. If = 2 then 8-hour average concentrations are printed. If = 3, a top 50 and high 2 table are prepared for this averaging time. If = 4, both the top 50, high 2 and every 8-hour average concentration are printed. This option is not available and this switch is ignored when the met. option switch = 3. Default is 1.
20	I1	24-Hour OutputSwitch. If = 1 then 24-hour average concentrations are not printed. If = 2 then 24-hour average concentrations are printed. If = 3, a top 50 and high 2 table are prepared for this averaging time. If = 4, both the top 50, high 2 and every 24-hour average concentration are printed. This option is not available and this switch is ignored when the met. option switch = 3. Default is 1.
22	I1	Long-term Output Switch. If = 1 then average concentrations over the entire meteorological data base provided are not printed. If = 2 then such long term average concentrations are printed. If = 3, a top 50 table is prepared for this averaging time. If = 4, both the top 50, the long-term average concentration are printed. This option is not available and this switch is ignored when the met. option switch = 3. Default is 1.

Card 3 STAR Data (These Cards are only read if Met. Option Switch = 3)

Col	Format	Information
1-60	6F10.0	A total of 96 cards are read here with the information being the frequency of winds for each combination of wind speed class, wind direction class and atmospheric stability class. Each card contains six values corresponding to the six possible wind speed classes. The order of the cards is 16 cards for the 16 possible wind direction classes for the first stability class, followed by the next 16 cards for the second stability class, followed by 16 cards for each subsequent stability class up to the final (sixth) stability class. The wind direction cards are ordered with north being first, north-northeast being second and proceeding clockwise until north-northwest is entered. Stabilities start with Turner Class A, and proceed to Turner Class F. The sum of all 576 values entered here should be 1.0.

Card 4 Mixing Heights for each Stability Class when using a STAR (This Card is only read if Met. Option Switch = 3)

Col	Format	Information
1-60	6F10.0	Six values are read here to indicate the characteristic mixing height to be used with each stability class when using a STAR for input meteorological data. Mixing heights should be entered in meters above ground.

Card 5 Characteristic Wind speeds for each wind speed class when using a STAR (This Card is only read if Met. Option Switch = 3)

Col	Format	Information
1-60	6F10.0	Six values are read here to indicate the characteristic wind speed to be used by the model for each of the wind speed classes when running with meteorological data entered in the form of a STAR. Wind speed values should be entered in meters per

second.

Card 6 Integer Parameters

Col	Format	Information
1-5	**I5**	**Number of Sources (maximum 121)**
6-10	**I5**	**Number of Receptors (maximum 1200)**
11-15	**I5**	**Number of Particle Size Classes, with a maximum of 20 allowed. Note that in order to compute any deposition values or to compute any concentrations which have deposition accounted for, this parameter must be set to some value other than 0.**
16-20	I5	Number of Hours of Meteorological data to be processed in this run.

Card 7 Real Parameters

Col	Format	Information
1-10	F10.0	ATIM - the length of time in one unit of meteorological data entry in minutes. Generally, this is entered as 60.
11-20	F10.0	Surface Roughness Height in cm (see Figure 1).
21-30	F10.0	SCAL - a scaling factor for all entries involving distance. The model assumes all entries for coordinates or dimensions are in meters. If the user desires to enter some other units, he may enter a conversion factor here such that when the units he has entered are multiplied by SCAL the result will be in meters.
31-40	F10.0	PD - the global value for density of the particulate matter in grams per cubic meter. Typical values range from 1.0 to 3.0 depending on the type of material which comprises the particulate matter. Entered here is a global value to be used for all sources, unless a different value is specified for a particular source later by the user.

Card 8 Meteorological Data Selection Switches. These cards are

entered only if a sequentially pre-processed meteorological data set is being used (Meteorological Data Option Switch = 2). The switches allow the user to select certain days of the sequential data set for processing and skip the rest.

Col	Format	Information
1-80	80I1	A series of 1's or zero's is used to determine if a particular day from the sequentially pre-processed meteorological data set is to be processed in this run. The first number entered corresponds to day 1, etc. A total of 366 values (4 and 1/2 cards) is needed to enter all 366 values. If a 1 is entered the day is to be processed, if a zero is entered the day is to be skipped.

Card 9 Characteristic Particle Diameters (not entered if the Number of Particle Size Classes is 0)

Col	Format	Information
1-10	8F10.0	The average or typical diameter for each particle size class is entered here in micrometers (um or meters X 10^{-6}). [Note these values are not multiplied by SCAL] A total of 20 particle size classes can be specified and a characteristic diameter must be specified for each particle size class used. Eight values can be placed on each card here. Use as many cards as necessary to provide the number of particle size classes specified, but do not include any blank cards.

Card 10 General Particle Size Distribution (not entered if the Number of Particle Size Classes is 0)

Col	Format	Information
1-10	8F10.0	The fraction of the emissions which are contained in each particle size class are entered here. A total of 20 particle size classes can be specified and a fraction must be specified for each particle size class used. 8 values can be placed on each card here. Use as many cards as necessary to provide the number of particle size classes specified, but do not include any blank cards. This card refers to a

general particle size distribution which is used for all sources here unless over-ridden by a specific switch entered on each source card. When over-ridden on the source cards which follow, the user may specify a specific size distribution to use for a specific source, or may have the model assume no deposition for a specific source.

Card 11 Gravitational Settling Velocities. This card is only entered if the number of particle size classes is greater than zero and the deposition parameters option switch is set to 2. Otherwise, the model computes gravitational settling velocities automatically. This option is only used if the user has some reason to use specialized gravitational settling velocities.

Col	Format	Information
1-10	8F10.0	The gravitational settling velocities in m/sec are entered here. A total of 20 particle size classes can be specified and a gravitational settling velocity must be specified for each particle size class used. Eight values can be placed on each card here. Use as many cards as necessary to provide the number of particle size classes specified, but do not include any blank cards.

Card 12 Deposition Velocities. This card is only entered if the number of particle size classes is greater than zero and the deposition parameters option switch is set to 2. Otherwise, the model computes deposition velocities automatically. This option is only used if the user has some reason to use specialized deposition velocities.

Col	Format	Information
1-10	8F10.0	The deposition velocities in m/sec are entered here. A total of 20 particle size classes can be specified and a deposition velocity must be specified for each particle size class used. Eight values can be placed on each card here. Use as many cards as necessary to provide the number of particle size classes specified, but do not include any blank cards.

Card 13 Receptors

Col	Format	Information
1-10	F10.0	X-Coordinate of receptors in meters, or in units which will be converted to meters when multiplied by SCAL entered above.
11-20	F10.0	Y-Coordinate (units as above)
21-30	F10.0	Z-Coordinate. Note that the Z coordinate is not a terrain elevation, since FDM does not simulate any rough terrain effects. The value of Z here is used to represent the height of the receptor above the ground ("flagpole height").

Each receptor is entered on a single card. A total of 1200 receptors may be specified. Note, however, that POSTZ will only accept a maximum of 200 receptors, thus if post-processing is to be used, the number of receptors should not exceed 200.

Card 14 Source Information. Source information is entered on a series of cards -- one card for each source. A total of 121 sources can be entered.

Col	Format	Information
2	I1	Type of source. 1 = point source, 2 = line source, and 3 = area source.
3	I1	Particle size override switch. If this switch is left blank or set to 0, the model uses the particle size distribution specified in card 10 to apply to this source. If, however, this value is set to 1, the model reads a second card (or as many cards as necessary), after card 14 to specify the particle size distribution for this source. If this value is set to 2, the model assumes no deposition for this source.
4-15	F12.0	Emission rate. For point sources, the units are grams per second (g/sec). For line sources the units are grams per meter per second (g/m-sec). For area sources the units are grams per square meter per second (g/m^2-sec). Note if this source is a wind-speed dependant

		source, the emission rate entered here is the proportionality constant of the wind speed dependant expression of the form: $E = Q_0u^w$ where E is the emission rate, Q_0 is the proportionality constant, u is the wind speed in m/sec and w is the wind speed dependance factor.
16-20	**F5.0**	**Wind speed dependance factor. See the note under emission rate above. If the source is not a function of wind speed, leave this column blank and enter the emission rate in columns 3-15 as above.**
21-30	F10.0	X-coordinate. For point sources, this is the x-coordinate of the source. For line sources, this is the x-coordinate of one end of the line source. For area sources, this is the x-coordinate of the center of the area source. In all cases the values are in meters, or in units which will be converted to meters when the computer multiplies by the value entered for SCAL above.
31-40	F10.0	Y-coordinate. For point sources, this is the y-coordinate of the source. For line sources this is the y-coordinate for one end of the line source (the same end as the above x-coordinate). For area sources, this is the y-coordinate of the center of the area source. In all cases the values are in meters, or in units which will be converted to meters when the computer multiplies by the value entered for SCAL above.
41-50	F10.0	2nd X-coordinate. For point sources, this column is not used. For line sources, this is the x-coordinate for the other end of the line source. For area sources, this is the x-dimension of the area source. If the area source is rotated, one of the axes must be selected as the x-axis, and it's rotation angle from the true x-axis entered below. The dimension of the side of the area source selected to represent the x axis is entered

		here. In all cases the values are in meters, or in units which will be converted to meters when the computer multiplies by the value entered for SCAL above.
51-60	**F10.0**	**2nd Y-coordinate. For point sources, this column is not used. For line sources, this is the y-coordinate for the other end of the line source. For area sources, this is the y-dimension of the area source. As noted for the x-axis above, the y dimension for rotated area sources is the dimension of the side of the area source selected to be the** y dimension. In all cases the values are in meters, or in units which will be converted to meters when the computer multiplies by the value entered for SCAL above.
61-70	F10.0	Height of emission. The release height for the emissions from this source in meters, or in units which will be converted to meters when the computer multiplies by the value entered for SCAL above. There is no plume rise in FDM, thus for a source with plume rise, the plume rise must be computed manually and added to the stack height and entered here.
71-75	F5.0	Source width or area source rotation angle. For line sources this parameter refers to the width of the line source in meters, or in units which will be converted to meters when the computer multiplies by the value entered for SCAL above. For area sources, this parameter is the number of degrees that the axis of the x dimension entered above is rotated from zero. This angle can have a value from -90 degrees to +90 degrees.
76-80	F5.0	Source-specific particle density. If a value of zero is entered here, or the space is left blank, the model will used the globally-specified density on Card 7 for this source. If however, the users wishes the source to have a different density, it is entered

here.

Card 14A Optional Particle Size data for Source. If the particle size switch in column 3 of the source card is set to 1, then this card (or group of cards) is read, otherwise, this card (or cards) is not read and should not be included. This card (or cards) specifies the particle size distribution for this source only and follows the exact same format as Card 10.

Col	**Format**	**Information**
1-10	**8F10.0**	**The fraction of the emissions which are contained in each particle size class are entered here. A total of 20 particle size classes can be specified and a fraction must be specified for each particle size class used. Eight values can be placed on each card here. Use as many cards as necessary to provide the number of particle size classes specified, but do not include any blank cards.**

Card 15 Meteorological data. Meteorological data are entered only if the met option switch is set to 1. If meteorological data are to be entered here, each hour of data is entered on a separate card. Note that none of the meteorological values are affected by the specification of SCAL above.

Col	Format	Information
1-10	F10.0	Wind speed in m/sec.
11-20	F10.0	Wind direction -- the direction in degrees from north from which the wind is coming.
25	I1	Stability class, where 6 values are possible and reflect Turner classes A-F, and 1=A, 2=B, 3=C, 4=D, 5=E and 6=F.
31-40	F10.0	Mixing Height in meters.
41-50	F10.0	Ambient Temperature in degrees Kelvin.

4.0 VALIDATION/SAMPLE RUNS

Three validation studies were performed using measured air quality and meteorological data. Two of these were for major surface mining operations and include both a western surface mine and an eastern surface mine. The third validation study was performed using data collected over a number years at the Hanford reservation in eastern Washington and generally termed the "Hanford 67" data base. Appendix A details the validation studies and their results. As the appendices indicates, the FDM model offers improved performance over the currently available model for fugitive dust impact assessment, the Industrial Source Complex Model.

Appendix B provides samples of input and output streams for the FDM Model.

Appendix C contains sections from the CALINE3 User's Guide for further documentation on the line source algorithm in the FDM.

Appendix D (bound separately) contains a complete listing of the FORTRAN code for the FDM Model. The version of the code contained in the appendix is that used for IBM-PC computers. Some minor changes would be necessary to generate a mainframe computer code from the code contained in the appendix.

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Fugitive Dust Model (FDM)
First Validation Study

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45

Table of Contents

1.0 Introduction.......... A(1)-1

2.0 Methodology and Model Inputs.......... A(1)-3

3.0 Air Quality Modeling Results.......... A(1)-11

4.0 Conclusions.......... A(1)-25

References.......... A(1)-27

1.0 INTRODUCTION

The Fugitive Dust Model (FDM) was developed specifically for computing concentrations and deposition rates of particulate matter from fugitive dust sources. This document details a validation study of the model. Model predictions were computed using daily emission data and on-site meteorology from a major source of fugitive dust (a western surface mining operation), and the results were compared with measured values for the same period. Similar computations were performed with the current model recommended by EPA in the Guideline on Air Quality Models -- the Industrial Source Complex (ISC) Model.

The FDM Model is designed specifically for computation of the impacts of fugitive dust sources. It has been under development for many years in several formats. The primary use of the model is for the computation of concentrations and deposition rates resulting from emission sources such as open pit mining operations or hazardous waste sites where fugitive dust is a concern. The model contains no plume rise algorithm and is thus not aimed at handling significant buoyant sources. It was recognized from the start that ultimate acceptance of the model would hinge on its ability to accurately predict concentrations from fugitive dust sources. To that end, a model validation effort was conceived using actual fugitive dust emissions and measured particulate concentrations. This report documents the findings of the validation exercise.

The current report is organized into three sections, in addition to this introduction. Section 2.0 describes the methodology, and the key modeling input values such as the model layout used in the current study. Section 3.0 discusses the modeling results and compares the values to measured values. Finally, Section 4.0 presents the conclusions of the investigation.

2.0 METHODOLOGY AND MODEL INPUTS

Both FDM and ISC are capable of predicting average concentrations of both Total Suspended Particulate Matter (TSP) and particulate matter less than 10 micrometers in mass mean diameter (PM-10) for a variety of averaging times. The averaging periods of interest are those for which standards or PSD increments are in effect. In most air quality permitting investigations, the period of greatest concern for fugitive dust impacts is the 24-hour average, since both a National Ambient Air Quality Standard (NAAQS) and a PSD increment exist for 24-hour PM-10 and TSP concentrations. Although a similar standard exists for annual-average concentrations, the experience gained from the conduct of air quality permitting investigations indicates that most fugitive dust emitting projects have far more difficulty demonstrating compliance with the 24-hour criteria than the annual criteria. As a result, this investigation focuses on 24-hour average concentrations. For the FDM model one version of the program deals with all averaging times, but for the ISC model separate versions are available for computing short- and long-term averages. The ISCST (for Short Term) version of the ISC Model was used in this investigation.

The current validation exercise was conducted using data obtained from a large western surface coal mining operation. The mining operation was selected for the validation study for the following reasons:

- Mining operations are major sources of fugitive dust, and have been the subject of numerous air quality studies and investigations dating back to the early 1970's. Published emission factors are available for most mining sources, and most western air pollution agencies have had to deal with the complex problems associated with computing mining fugitive dust impacts.

47

- **The mining industry and the particular mining company in question were very cooperative in providing the data and information necessary for the model validation.**

- **The mine in question is a large operation and has an extensive monitoring network for measurement of both PM-10 and TSP concentrations at a total of 5 stations located in the immediate area of the mine. Many have referred to the mine as the "most monitored mine in the history of the industry".**

- **In addition to the air quality data, on-site meteorological data were available for the validation investigation.**

- Both the air quality and meteorological data are collected in compliance with the full requirements of a PSD monitoring network, including quality assurance provisions. The data are routinely submitted to the local air pollution agency as part of the permit for the mining operation.

Data were obtained from the mining company for a period of one entire dry season, April through September of 1986. Since sampling was conducted on a six-day cycle for TSP and PM-10, a total of 32 case days were available for the validation study.

The emission inventory for the current investigation was computed for each of the 32 case days studied. Published emission factors taken from the literature were used in the analysis. Generally, reliance was made on the EPA's emission factor reference, Document AP-42. The mining company provided the input information needed to compute the emissions from the factors for each of the 32 case days. Information provided by the mining company included tonnage mined, transported and processed (crushed) on each day, and the tonnage and locations for disposal of the waste material removed on each day. Other general information on the equipment in use at the mine and the schedule for each item were also provided.

The emissions from the mining operation were divided into a total of 56 separate sources for FDM input, based on the actual layout of the mine. For the haul roads, a total of 27 separate sections of road were identified, and the

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The emissions from the mining operation were divided into a total of 56 separate sources for FDM input, based on the actual layout of the mine. For the haul roads, a total of 27 separate sections of road were identified, and the actual truck traffic identified for each section. Emissions were computed for each section of road based on the activity on that section of road for each case day. Figure 2-1 illustrates the location of the sources as defined by the FDM Model.

For the ISC model runs, it was not possible to use the same emission source layout as the FDM runs, since ISC does not have the capability to treat line sources directly. As a result, each of the FDM line sources was broken into a series of volume sources for ISC input. Also, ISC does not have the capability to treat rectangular area sources, so the area source layout was revised for square area sources only. For the ISC runs a total of 170 individual sources were used in the modeling. The total emissions for each case day were identical in the FDM and ISC model inputs.

Particle size distributions assumed in the modeling consisted of five separate particle size classes: 0-2.5, 2.5-5, 5-10, 10-15 and >15 micrometers. The modeling results were interpreted in terms of both the total suspended particulate (TSP) concentrations (the sum of all particle size classes) and the concentration of particles 10 micrometers and smaller in mass mean diameter (PM-10). The PM-10 concentrations were computed as the sum of the first three particle size classes from the modeling. Particle size distributions of emitted sources were obtained from literature measurements of particle size distributions in the vicinity of mining operations, including the PEDCo and MRI (EPA, 1981) investigation of surface mine emissions in 1981, and particle size distributions reported in EPA's Complilation of Air Pollutant Emission Factors (EPA, 1985).

A total of five air quality monitoring stations are located in the project area. The stations are identified by number. The locations of the stations are shown in Figure 2-1. Following are descriptions of each of the stations:

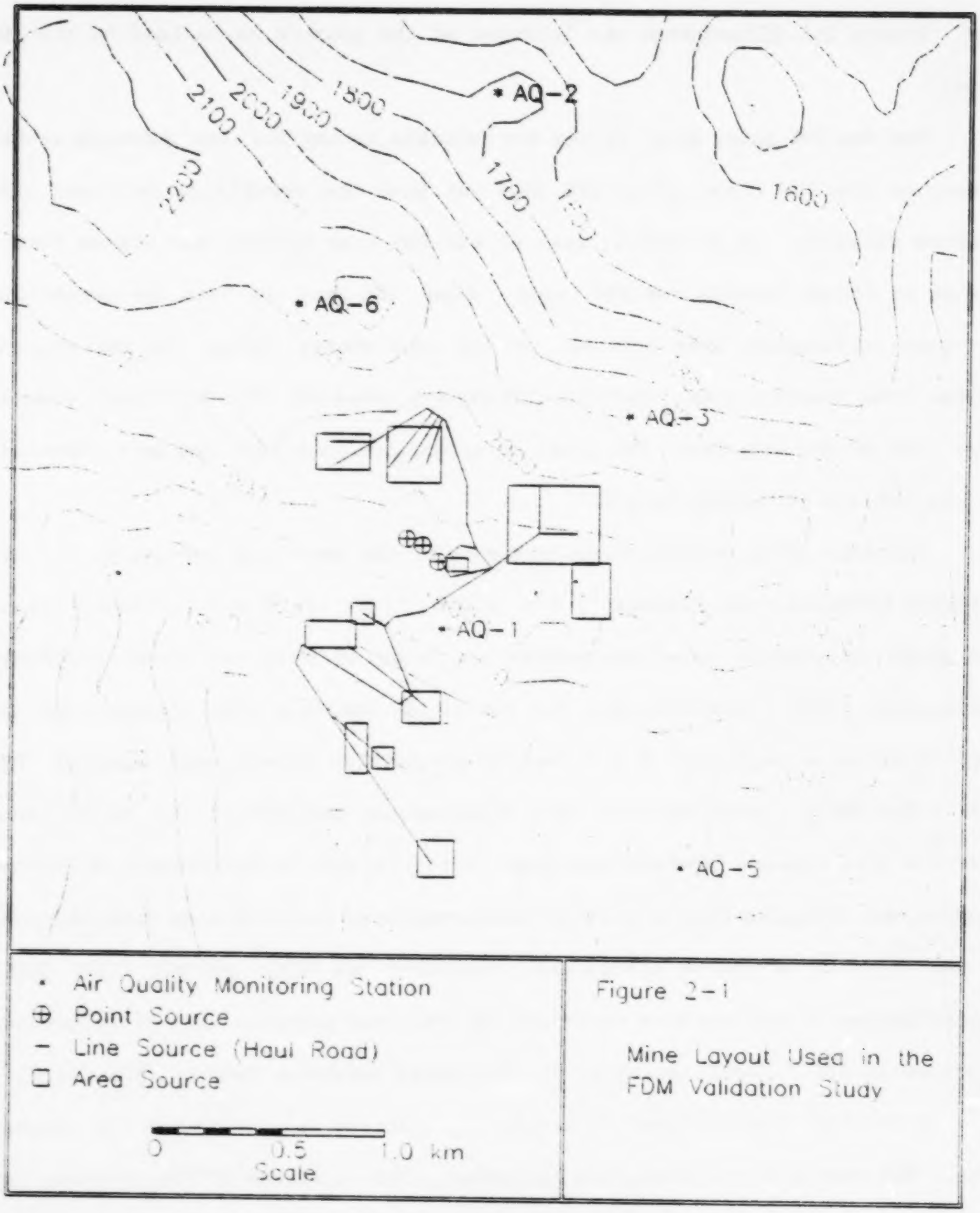
2200
2100
2000
1900
1800
AQ-2
1700
1600
AQ-6
AQ-3
AQ-1
AQ-5
• Air Quality Monitoring Station
⊕ Point Source
— Line Source (Haul Road)
☐ Area Source
0
0.5
1.0 km
Scale

Figure 2-1

Mine Layout Used in the FDM Validation Study

- **AQ-1 Located in the center of the mining operation by the haul road to the waste dump. The station consists of two co-located PM-10 monitors and a meteorological station.**
- **AQ-2 Located atop the ridge to the north of the mine. It is often a background station, with little impact from the mine. Equipment consists of a PM-10 monitor and a TSP monitor.**
- AQ-3 Located to the east of the major mining operations. Equipment includes a PM-10 monitor and two co-located TSP monitors.
- AQ-5 Located to the south of the mine. It consists of a PM-10 monitor and a TSP monitor.
- AQ-6 Located to the north west of the mining operation on a hill. Equipment consists of a PM-10 monitor and a TSP monitor.

Measured PM-10 and TSP data at the five monitoring stations were compiled by the mining company and transmitted to TRC in hard copy and floppy disk format. TRC extracted the case days from the overall particulate data and input the values to a "spread-sheet" program for comparison with the model predictions.

The ultimate goal of this investigation was to compare the model predictions to these measured data. The modeled concentrations, however, contain only the contribution of the mining operation to the ambient particulate levels, while the monitored values contain all particulates, whether from the mine or not. The "background" contribution to the particulate loading is highly variable and difficult to quantify. The approach taken here for estimation of background concentrations was to scan all five measured values for each case day, and select the lowest value as the background. The modeled concentrations, discussed in the next chapter, are added to the background for each day to determine the total impact for comparison to the measured values.

Meteorology is measured at several locations in the vicinity of the mine.

Two candidate locations were considered for the air quality modeling study: a monitor location near AQ-1 and a monitor location near AQ-6 (see Figure 2-1). Ultimately the AQ-1 meteorology data were selected based on the quality of the data and the representative nature of the wind speed and wind direction data to the mine emission sources. Examination of Figure 2-1 shows the location of the monitor to be central to the emitting sources at the mine.

Both the FDM and ISC models require information on the hourly values for wind speed, wind direction, temperature, atmospheric stability and mixing height. Wind speed, wind direction and temperature are measured directly by the sensors at AQ-1. Atmospheric stability is a measure of the turbulent mixing capacity of the atmosphere and was estimated for the current investigation from the standard deviation of the wind direction, also recorded at AQ-1, and from the wind speed and time of day. Stability is expressed as one of 6 classes labeled A through F, where A is the least stable (greatest turbulent mixing) and F is the most stable (least turbulent mixing). The conversion from standard deviation of the wind direction, wind speed and time of day to stability is accomplished as follows (taken from EPA, 1987):

Intital Estimate of Stability Class is provided by:

Standard Deviation	Stability Class
> 22.5	A
17.5 - 22.5	B
12.5 - 17.5	C
7.5 - 12.5	D
3.75 - 7.5	E
< 3.75	F

Stability Classes are Adjusted by time of day and wind speed by:

Time of Day	Initial Stability	Wind Speed (m/sec)	Final Stability
Daytime	A	$U < 3$	A
		$3 \le U < 4$	B
		$4 \le U < 6$	C
		$6 \le U$	D
	B	$U < 4$	B
		$4 \le U < 6$	C
		$6 \le U$	D
	C	$U < 6$	C
		$6 \le U$	D
	D, E or F	Any	D
Nighttime	A	$U < 2.9$	F
		$2.9 \le U < 3.6$	E
		$3.6 \le U$	D
	B	$U < 2.4$	F
		$2.4 \le U < 3.0$	E
		$3.0 \le U$	D
	C	$U < 2.4$	E
		$2.4 \le U$	D
	D	Any	D
	E	$U < 5.0$	E
		$5.0 \le U$	D
	F	$U < 3.0$	F
		$3.0 \le U < 5.0$	E
		$5.0 \le U$	D

For fugitive dust impacts, results are generally very insensitive to values used for mixing height because the emissions are released at or near the ground, and the impacts are generally very close to the source. As a result the emissions have little opportunity to mix vertically to the height of the mixing layer. To provide the models with values for these required values, mixing heights were assigned by stability class using the following general values:

Stability Class	Mixing Height (m)
A	
B	1,600.
C	1,200.
D	800.
E	400.
F	10,000.
	10,000.

3.0 AIR QUALITY MODELING RESULTS

The FDM and ISC models were run for the 32 case days identified earlier and the predicted concentrations, both PM-10 and TSP, computed as the sum of the modeled concentration and the background as discussed earlier. The results are presented in two formats here. First, the measured versus predicted values are shown in Tables 3-1 through 3-4 for FDM TSP, ISC TSP, FDM PM-10 and ISC PM-10 respectively. Second, a "scatter plot" of the measured and predicted values for these same four cases are shown in Figures 3-1 through 3-4. The scale of the four plots are all identical.

The performance of each model is generally good for most of the days given the usual accuracy of air quality models. However, the figures show a tendency on the part of ISC for TSP over-predictions on a few case days. It is these case days which are of greatest concern to regulators, since the 24-hour TSP standards and PSD increments refer only to the highest one or two days per year. The PM-10 results are much closer for the two models. Since PM-10 represents the smaller particles which would be expected to encounter less deposition than the TSP particles, the FDM and ISC Model predictions would be expected to be closer for PM-10.

A number of different techniques, including cumulative frequency plots, and various statistical functions have been used in the past to evaluate air quality model performance. Air quality models are frequently quoted to predict within a factor of two, thus one means of comparison is to determine what number of the data points are within a factor of two. For FDM, the TSP predicted results are

Table 3-1. Comparison of Measured and FDM Predicted TSP Concentrations (ug/m3)

		AQ-2		AQ-3		AQ-5		AQ-6	
Day	Date	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.
1	3/21/86			22.7	38.3	35.8	11.1	11.1	14.8
2	3/27/86	40.9	39.5					39.3	53.1
3	4/8/86	9.6	8.7			22.6	11.1	7.6	9.7
4	4/14/86	14.8	10.9	40.0	43.8	10.5	9.8	9.8	13.9
5	4/20/86	23.2	15.7	21.2	15.4	17.9	15.3	15.3	15.3
6	4/26/86	13.5	10.9	14.3	10.9	16.2	11.4	10.9	10.9
7	5/2/86	7.9	8.6	14.9	94.4	5.8	4.7	4.7	4.7
8	5/8/86	10.2	9.4	10.1	9.4	17.3	9.5	9.4	9.4
9	5/14/86	19.9	18.2	18.3	18.3	33.1	23.3	18.2	18.2
10	5/20/86	11.9	6.1	44.0	23.9	16.1	11.7	6.1	6.1
11	5/26/86	11.7	8.4			11.5	9.3	8.4	8.4
12	6/1/86	36.6	27.6			27.5	27.7	37.7	27.6
13	6/7/86	20.2	18.3	26.7	18.5	33.0	19.1	18.3	18.3
14	6/13/86	34.8	28.7	48.8	61.2	27.3	27.5	58.0	46.0
15	6/19/86	13.8	13.8	23.9	24.8	29.2	15.0	15.5	13.8
16	6/25/86	37.2	39.3	76.2	66.0			34.5	45.7
17	7/2/86	27.6	25.9	43.0	42.4	30.7	27.2	25.1	25.9
18	7/7/86	25.4	18.7	64.8	76.3	17.3	17.3	21.8	28.4
19	7/13/86	36.7	31.1	46.9	31.1	31.1	31.1	32.0	32.2
20	7/19/86	32.2	28.5	35.5	31.4	31.7	32.1	28.3	28.3
21	7/25/86	22.6	15.9	33.5	40.3	15.4	15.4	25.7	58.9
22	7/31/86	34.3	29.3	58.7	46.1	34.5	34.9	28.9	30.7
23	8/6/86	41.6	30.9	57.8	54.1	29.5	28.0	28.0	37.9
24	8/12/86	36.8	30.5	52.1	47.6	53.8	31.4	30.1	31.6
25	8/18/86	27.6	19.1	57.2	51.8	26.6	19.8	18.9	23.0
26	8/24/86	36.9	28.2	45.4	28.2	35.5	28.3	28.2	28.2
27	8/30/86	28.9	27.2	32.5	27.4	45.7	27.2	27.1	27.1
28	9/5/86					64.4	32.5	25.7	26.6
29	9/11/86					52.7	33.0	32.3	44.3
30	9/17/86					9.5	6.0	4.7	4.7
31	9/23/86					37.7	33.9	26.9	45.9
32	9/29/86					30.5	12.9	12.9	13.4

Table 3-2. Comparison of Measured and ISC Predicted TSP Concentrations (ug/m3)

		AQ-2		AQ-3		AQ-5		AQ-6	
Day	Date	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.
1	3/21/86			22.7	49.3	35.8	11.1	11.1	24.6
2	3/27/86	40.9	39.4					39.3	79.8
3	4/8/86	9.6	9.6			22.6	16.8	7.6	11.1
4	4/14/86	14.8	10.8	40.0	41.6	10.5	9.8	9.8	19.2
5	4/20/86	23.2	16.9	21.2	15.4	17.9	15.3	15.3	15.3
6	4/26/86	13.5	10.9	14.3	10.9	16.2	11.4	10.9	10.9
7	5/2/86	7.9	8.9	14.9	83.7	5.8	4.7	4.7	4.7
8	5/8/86	10.2	9.4	10.1	9.4	17.3	9.4	9.4	9.4
9	5/14/86	19.9	18.2	18.3	18.2	33.1	23.8	18.2	18.2
10	5/20/86	11.9	6.1	44.0	25.3	16.1	20.2	6.1	6.1
11	5/26/86	11.7	8.4			11.5	9.7	8.4	8.4
12	6/1/86	36.6	27.6			27.5	28.0	37.7	27.6
13	6/7/86	20.2	18.3	26.7	18.5	33.0	19.4	18.3	18.3
14	6/13/86	34.8	29.2	48.8	80.3	27.3	27.7	58.0	73.5
15	6/19/86	13.8	13.8	23.9	34.8	29.2	15.0	15.5	13.8
16	6/25/86	37.2	48.1	76.2	61.6			34.5	62.6
17	7/2/86	27.6	25.9	43.0	40.6	30.7	29.3	25.1	25.9
18	7/7/86	25.4	19.6	64.8	114.6	17.3	17.3	21.8	43.2
19	7/13/86	36.7	31.1	46.9	31.1	31.1	31.1	32.0	35.1
20	7/19/86	32.2	28.5	35.5	30.8	31.7	39.9	28.3	28.3
21	7/25/86	22.6	15.8	33.5	34.5	15.4	15.4	25.7	77.3
22	7/31/86	34.3	29.4	58.7	59.7	34.5	48.8	28.9	30.8
23	8/6/86	41.6	31.2	57.8	50.2	29.5	28.0	28.0	55.1
24	8/12/86	36.8	30.4	52.1	43.7	53.8	33.1	30.1	32.0
25	8/18/86	27.6	19.1	57.2	90.4	26.6	22.1	18.9	30.5
26	8/24/86	36.9	28.2	45.4	28.2	35.5	28.3	28.2	28.2
27	8/30/86	28.9	27.5	32.5	27.4	45.7	27.3	27.1	27.1
28	9/5/86					64.4	46.3	25.7	26.6
29	9/11/86					52.7	34.6	32.3	58.3
30	9/17/86					9.5	6.6	4.7	4.7
31	9/23/86					37.7	48.4	26.9	81.1
32	9/29/86					30.5	12.9	12.9	13.5

Table 3-3. Comparison of Measured and FDM Predicted PM-10 Concentrations (ug/m3)

		AQ-1		AQ-2		AQ-3		AQ-5		AQ-6	
Day	Date	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.
1	3/21/86	17.0	38.7	6.0	7.7	15.4	18.7	12.4	4.4	4.4	7.7
2	3/27/86	36.9	46.8	22.5	19.4					19.3	30.1
3	4/8/86	8.6	53.3	4.2	4.2	14.6	15.0	13.5	6.3	3.6	4.6
4	4/14/86	21.4	35.2	4.7	5.1	10.2	16.2	5.5	4.7	5.8	7.4
5	4/20/86	17.3	27.3	11.8	10.5	12.1	10.1	10.6	10.1	10.1	10.1
6	4/26/86	14.7	22.7	7.2	5.4	5.4	5.4	6.7	5.6	5.9	5.4
7	5/2/86	4.5	11.5	4.5	4.1	6.1	32.3	3.7	2.7	2.7	2.7
8	5/8/86	16.2	37.9	4.1	4.1	5.0	4.1	6.1	4.1	4.2	4.1
9	5/14/86	16.0	27.3	9.5	8.5	8.9	8.5	12.5	10.2	8.5	8.5
10	5/20/86	7.4	40.9	3.5	2.7	10.2	8.5	3.5	6.0	2.7	2.7
11	5/26/86	6.4	4.3			5.1	4.1	4.5	4.4	4.0	4.0
12	6/1/86	19.5	16.6	20.7	14.3	18.7	14.4	14.3	14.5	19.9	14.3
13	6/7/86	15.5	34.4	8.4	8.4	11.2	8.5	13.3	8.8	9.8	8.4
14	6/13/86	20.0	26.8			23.2	36.4	16.3	16.4	23.6	30.1
15	6/19/86	15.7	33.8	10.0	7.6	10.1	12.4	11.3	8.0	7.6	7.6
16	6/25/86	29.5	33.2	24.4	22.8	31.8	29.8	19.2	19.2	21.4	28.9
17	7/2/86	28.2	39.6	19.0	13.9	20.7	19.2	14.9	14.7	13.6	13.9
18	7/7/86	24.1	22.9	14.1	11.4	25.8	43.4	10.6	10.6	12.6	17.7
19	7/13/86	23.1	21.0	22.6	19.7	22.7	19.7	19.7	19.7		
20	7/19/86	24.9	40.1	19.9	17.3	18.8	18.2	18.7	20.5	17.2	17.2
21	7/25/86	12.0	12.6	13.8	10.7	15.5	18.4	10.5	10.5		
22	7/31/86	25.8	68.0	21.9	17.3	29.6	24.8	21.9	22.5	17.2	17.8
23	8/6/86	26.3	25.5	24.7	19.9	26.6	27.2	19.7	18.7	18.7	25.4
24	8/12/86	43.2	73.3	22.8	18.8	25.6	24.3	30.1	19.7	18.7	19.3
25	8/18/86	38.7	67.8	15.7	12.1	33.7	28.4	16.5	12.8	12.0	15.0
26	8/24/86	24.1	35.7	22.1	18.9	21.0	18.9			18.9	18.9
27	8/30/86	19.9	17.6	16.9	14.5	14.6	14.5	21.1	14.4	14.4	14.4
28	9/5/86	65.9	63.0					34.1	21.0	16.0	16.3
29	9/11/86	35.0	43.3					24.9	19.2	18.6	26.1
30	9/17/86	6.7	39.2					4.4	3.7	3.0	3.0
31	9/23/86	27.0	40.9							19.7	34.4
32	9/29/86	20.1	57.3					13.5	8.5	8.5	8.7

Table 3-4. Comparison of Measured and ISC Predicted PM-10 Concentrations (ug/m3)

		AQ-1		AQ-2		AQ-3		AQ-5		AQ-6	
Day	Date	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.
1	3/21/86	17.0	38.0	6.0	10.0	15.4	16.0	12.4	4.4	4.4	10.9
2	3/27/86	36.9	54.3	22.5	19.3					19.3	35.7
3	4/8/86	8.6	55.8	4.2	4.2	14.6	11.6	13.5	7.4	3.6	4.6
4	4/14/86	21.4	38.2	4.7	5.0	10.2	13.9	5.5	4.7	5.8	7.8
5	4/20/86	17.3	28.2	11.8	10.8	12.1	10.1	10.6	10.1	10.1	10.1
6	4/26/86	14.7	22.4	7.2	5.4	5.4	5.4	6.7	5.6	5.9	5.4
7	5/2/86	4.5	9.6	4.5	3.9	6.1	25.5	3.7	2.7	2.7	2.7
8	5/8/86	16.2	38.1	4.1	4.1	5.0	4.1	6.1	4.1	4.2	4.1
9	5/14/86	16.0	30.2	9.5	8.5	8.9	8.5	12.5	10.1	8.5	8.5
10	5/20/86	7.4	41.8	3.5	2.7	10.2	8.2	3.5	7.5	2.7	2.7
11	5/26/86	6.4	4.3			5.1	4.1	4.5	4.4	4.0	4.0
12	6/1/86	19.5	16.4	20.7	14.3	18.7	14.4	14.3	14.5	19.9	14.3
13	6/7/86	15.5	32.6	8.4	8.4	11.2	8.4	13.3	8.8	9.8	8.4
14	6/13/86	20.0	27.4			23.2	33.6	16.3	16.5	23.6	37.2
15	6/19/86	15.7	32.2	10.0	7.6	10.1	13.9	11.3	7.9	7.6	7.6
16	6/25/86	29.5	33.2	24.4	26.0	31.8	27.1	19.2	19.2	21.4	33.0
17	7/2/86	28.2	39.6	19.0	13.8	20.7	18.1	14.9	14.9	13.6	13.8
18	7/7/86	24.1	22.7	14.1	11.8	25.8	42.2	10.6	10.6	12.6	18.8
19	7/13/86	23.1	20.9	22.6	19.7	22.7	19.7	19.7	19.7		
20	7/19/86	24.9	41.7	19.9	17.3	18.8	17.9	18.7	22.3	17.2	17.2
21	7/25/86	12.0	12.2	13.8	10.6	15.5	16.0	10.5	10.5		
22	7/31/86	25.8	73.2	21.9	17.3	29.6	26.6	21.9	25.3	17.2	17.7
23	8/6/86	26.3	24.6	24.7	19.7	26.6	25.1	19.7	18.7	18.7	27.6
24	8/12/86	43.2	71.5	22.8	18.8	25.6	22.6	30.1	20.1	18.7	19.2
25	8/18/86	38.7	76.1	15.7	12.1	33.7	35.1	16.5	13.4	12.0	15.8
26	8/24/86	24.1	36.9	22.1	18.9	21.0	18.9			18.9	18.9
27	8/30/86	19.9	16.8	16.9	14.6	14.6	14.5	21.1	14.5	14.4	14.4
28	9/5/86	65.9	63.4					34.1	23.4	16.0	16.3
29	9/11/86	35.0	43.9					24.9	19.8	18.6	28.5
30	9/17/86	6.7	41.5					4.4	3.6	3.0	3.0
31	9/23/86	27.0	39.2							19.7	41.3
32	9/29/86	20.1	56.2					13.5	8.5	8.5	8.7

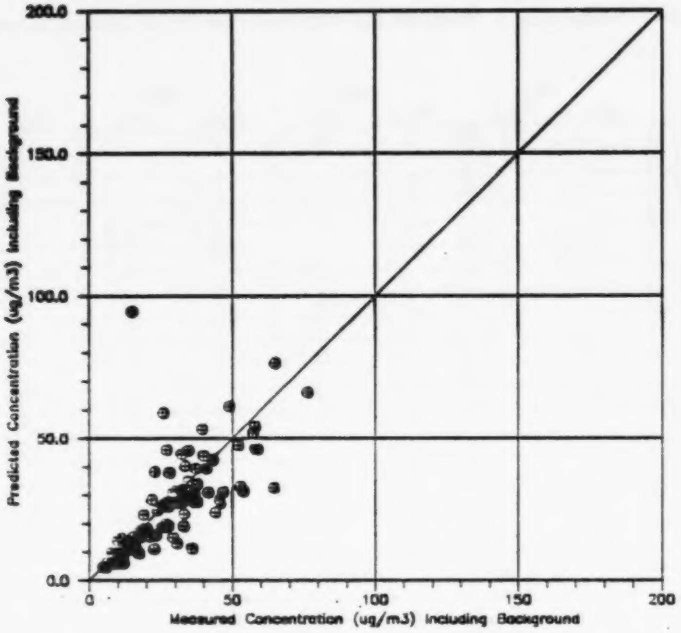

FIGURE 3-1 FDM EVALUATION FOR TSP

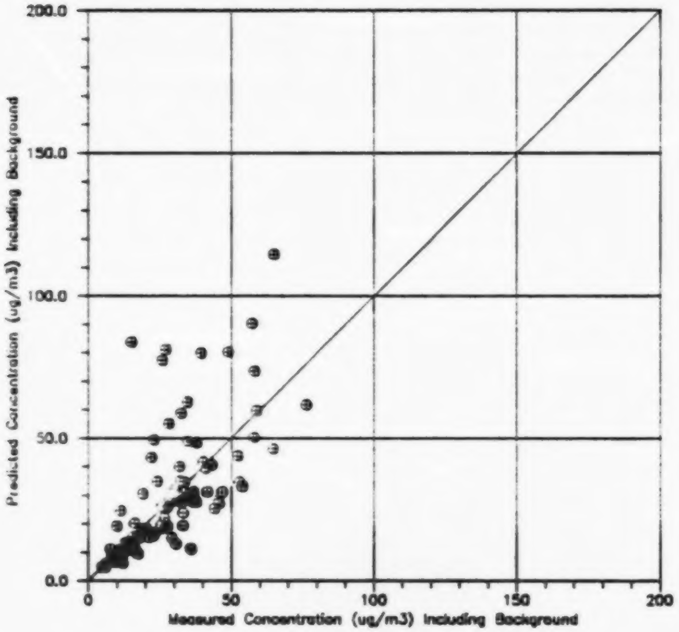

FIGURE 3-2 ISC EVALUATION FOR TSP

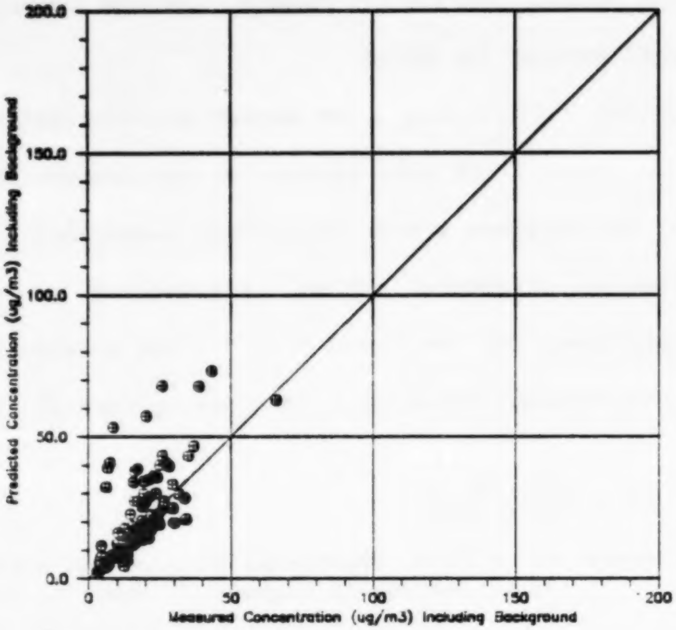

FIGURE 3-3 FDM EVALUATION FOR PM-10

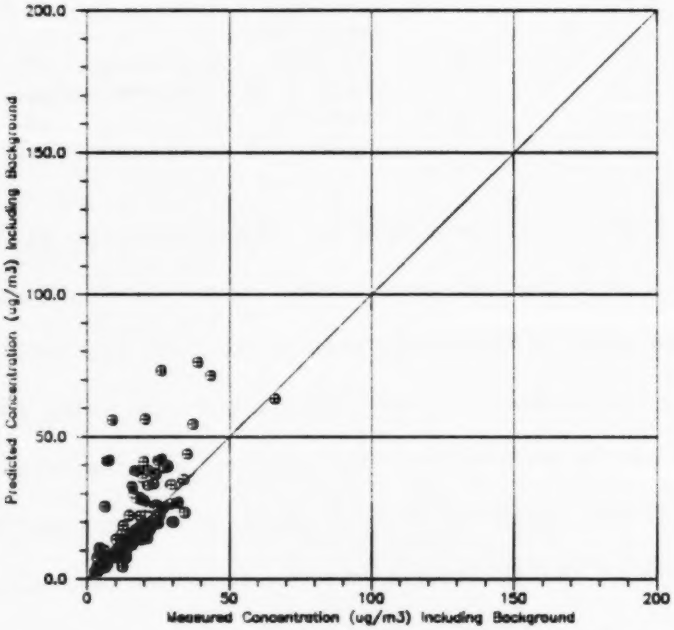

FIGURE 3-4 ISC EVALUATION FOR PM-10

within a factor of two of the measured results for 95 percent of the values. For the FDM PM-10 results, the measured and predicted values are within a factor of two for 91 percent of the values. For the ISC results, the same comparison shows 93 percent for TSP and 89 percent for PM-10.

EPA has recently been recommending a new method for evaluation of model performance (Cox et. al., 1988). It also centers on the concept of accuracy within a factor of two, but utilizes a more complicated comparison. There are two steps in the evaluation procedure. First, a screening computation is completed using two quantities, the fractional bias for the average values and a fractional bias for the standard deviation. They are defined as follows:

$$FB = \frac{OB - PR}{(OB + PR)/2}$$

where: FB = fractional bias of the average
OB = average of highest 25 observed values
PR = average of highest 25 predicted values

$$FO = \frac{S_o - S_p}{(S_o + S_p)/2}$$

where: FO = fractional bias of the standard deviation
S_o = standard deviation of the highest 25 observed values
S_p = standard deviation of the highest 25 predicted values

The screening evaluation is performed by computing both of the above parameters, and plotting on a special graph. The second level of analysis is more complex. The second level is called the statistical test and involves using the same fractional bias computation as above, but rather than using the average and standard deviations of the observed and predicted values, the technique uses a parameter called the robust estimate of the highest concentration (RHC). In addition, the computation of the fractional bias is done for several averaging

periods and differing meteorological conditions and the results used to compute a composite performance measure. Finally, a statistical technique called "bootstrapping" is used where values are extracted at random from the overall data set to create a "sampled" data set, which is used in the computation of these same performance measures. By conducting this random sampling many times, the statistician can determine if differences in model performance are statistically significant. More details on the technique can be found in Cox's paper.

Using the screening technique, for the TSP concentrations in the current model evaluation, the computed values for the FB for FDM was -0.018 and the FO was -0.270. For the PM-10 concentrations the FB for FDM was -0.364 and the FO was -0.309. For ISC, the TSP values were -0.246 for the FB and -0.559 for the FO, while for PM-10 the values were -0.400 for the FB and -0.357 for the FO. The values are plotted in Figures 3-5 and 3-6 for TSP and PM-10 respectively. The box at the center of the figure is an indication of the "factor of two" performance of the model. If the data plots within the box, then the model is said to have performed within a factor of two. Since the current model evaluation results for FDM show both TSP and PM-10 plot within the box, the model performance for FDM is judged to be within the customary factor of two that EPA and others use as a guide. Similarly, the results for ISC plot inside the box but the values are further from the center of the box than the FDM results. As was observed in the scatter plot comparison, the difference between FDM and ISC is greater for TSP than for PM-10.

The second level of performance evaluation was a more complex undertaking. The technique has been developed primarily for predicting concentrations of sulfur dioxide or other gaseous compounds for which the data available generally

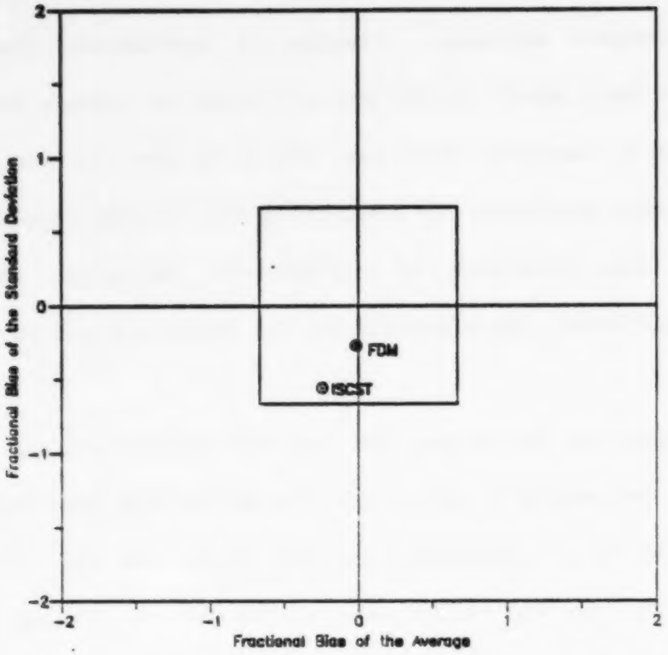

Figure 3−5. Screening Evaluation Results for TSP

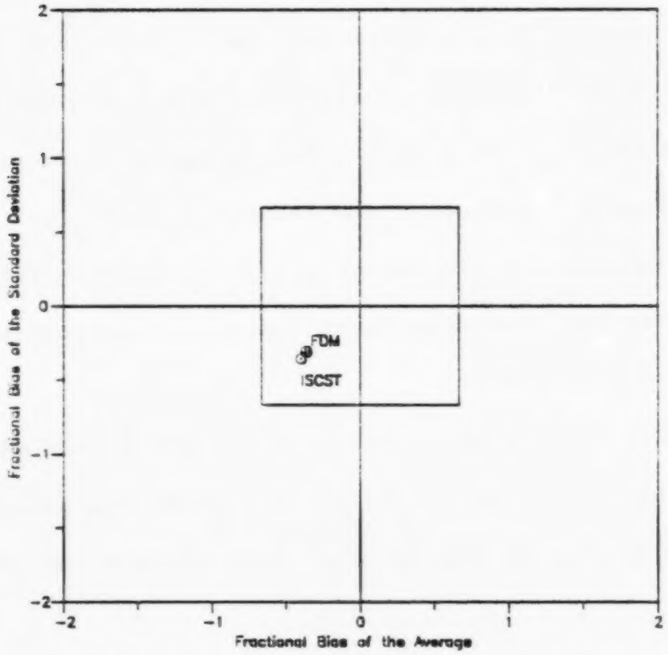

Figure 3−6. Screening Evaluation Results for PM−10

include hourly observations of SO_2 concentration and meteorology on a continuous basis for a year or more. The measurement of particulate usually is done in 24-hour integrated samples. As a result, modifications had to be made to the statistical evaluation methods to apply them to the current application. The modifications to the technique of Cox are summarized as follows:

- Only 24-hour values were available, thus only the only averaging time in the evaluation was 24-hour. Cox refers to a calculation of a "scientific" evaluation which uses 1-hour average concentrations. This computation was dispensed with. Given the single averaging time used here, the composite performance measure used here was equal to the Absolute Fractional Bias of the RHC values for the 24-hour samples.

- Since only 32 case days were examined, and since data were not available at all stations for all of the days, it was determined to combine all of the data into a single sampling set for the purposes of computing the RHC, rather than conducting the computation on a site-by-site basis as the guidance suggests. The data sets would have been too small if the separation of the values by site had been performed.

- The bootstrapping technique calls for the construction of a number of trial "years" by sampling the data set. Since sampling a six month, intermittent data set to create a full year of data, would extend the data beyond its measurement bounds, the sampling was performed only to create a trial set equivalent in size to the original data set. Thus for TSP, 111 values are in the original data set and each bootstrap sample was composed of 111 randomly-sampled values. Note that no persistance of 3 days was used since the data are sampled on a six-day cycle, and persistence is not relevant.

The bootstrapping analysis was completed for both TSP and PM-10 values for both models. Although not customarily presented in this fashion, the frequency distribution of the Fraction Bias of the RHC's calculated in the bootstrapping analysis for TSP are shown in Figure 3-7 and for PM-10 in Figure 3-8. Note that the figure presents the fractional bias, not the absolute fractional bias. As the figure shows, there is a separation between the FDM values and the ISC values for TSP, indicating a different performance. Note that the values for ISC are all negative, while the values for FDM are closer to zero, but predominantly

65

positive.

When the results for TSP and PM-10 are presented in the more customary fashion for 95% confidence limits, as shown in Figure 3-9, it is clear that the FDM Model is closer to reality than the ISC Model. However, there is considerable overlap between the confidence limits of the two models. Note that in Figure 3-9, the absolute value of the fractional bias is plotted.

The previous discussion would lead to the conclusion that generally, the FDM model performs better with the data than the ISC Model. In actuality, as earlier figures show, both models do reasonably well for the majority of data points. However, ISC has the tendency for over-prediction on few days. Unfortunately, it is these days which are the focus of the permitting regulations. Most regulations concern the maximum or second highest concentration, so the ISC over-prediction on these days causes very misleading results in air quality permitting studies. It tends to occur under stable, low wind speed conditions.

One of the major advantages of the FDM approach is the avoidance of these large over-predictions. The improved prediction occurs due to the superior deposition algorithm in the FDM Model. During low wind speed stable conditions, the ISC model allows very high concentrations to be predicted, not reflecting the deposition which would occur during the long travel times to the receptor. FDM more accurately represents the behavior of particles in the atmosphere.

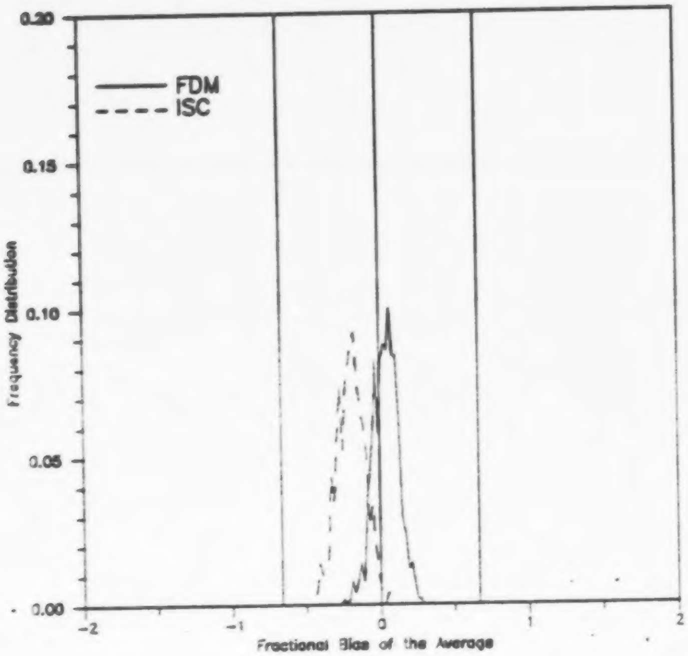

Figure 3-7. Fractional Bias Distributions for TSP

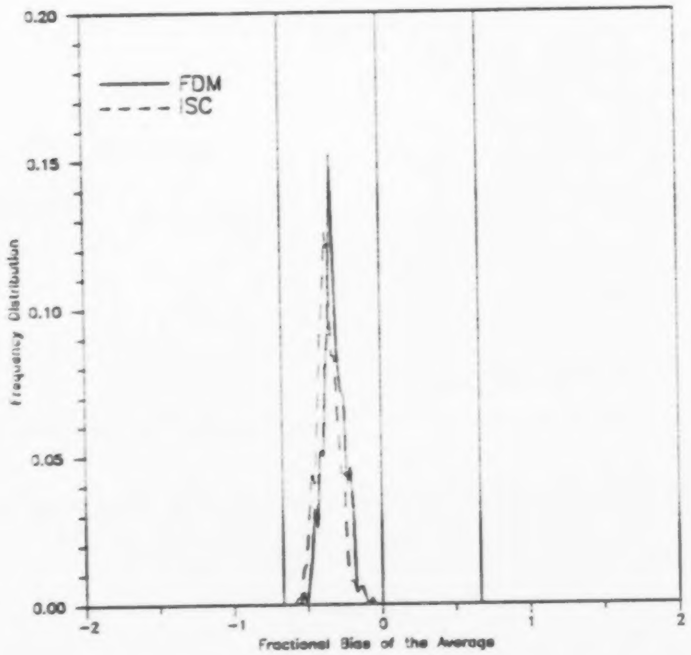

Figure 3-8. Fractional Bias Distributions for PM-10

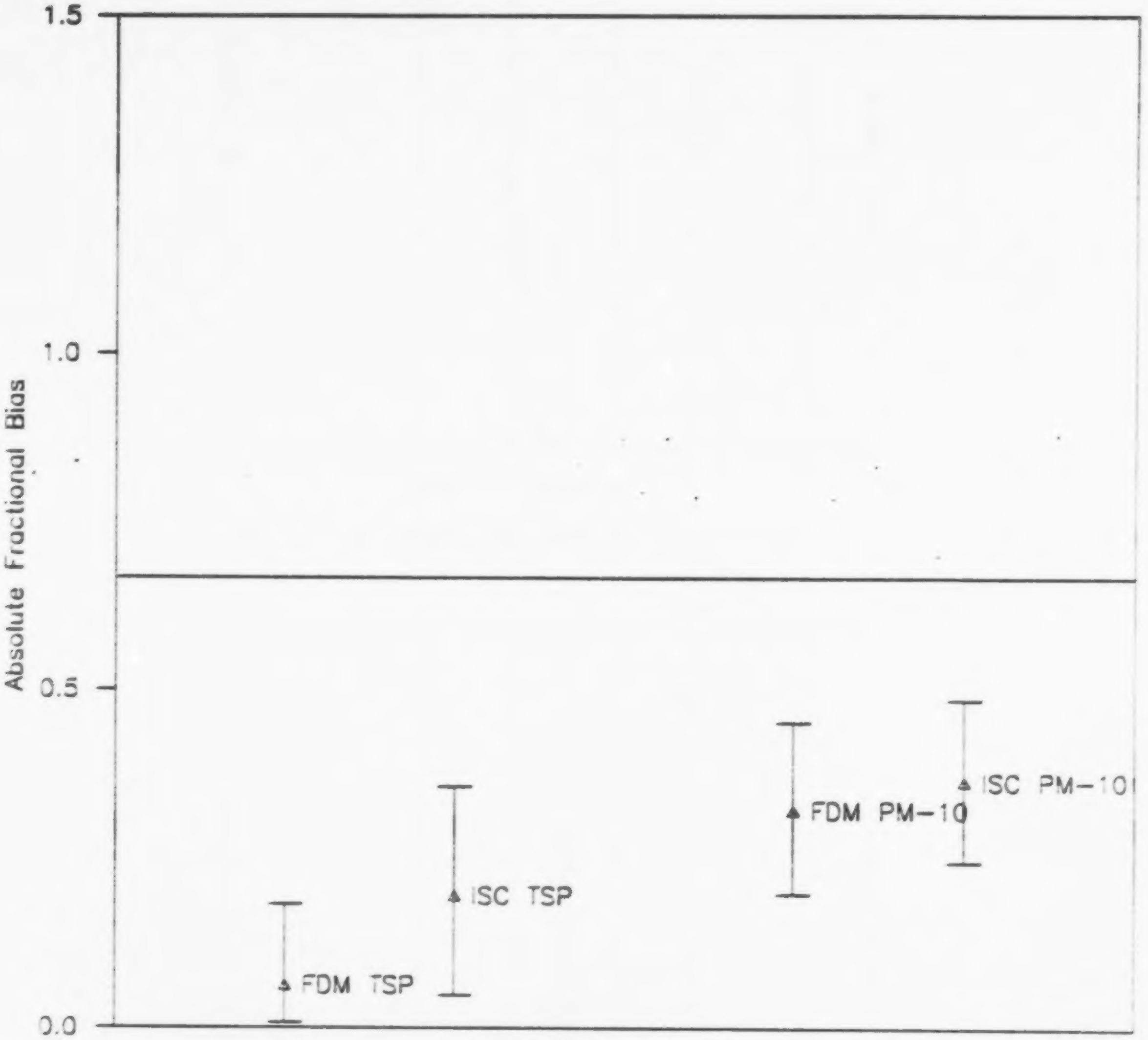

Figure 3-9. Absolute Fractional Bias at 95% Bootstrap Confidence Bounds

4.0 CONCLUSIONS

The previous analysis has determined that the FDM Model performs generally well in characterizing particulate concentrations in the vicinity of the fugitive dust source. The ISC model also performed well for the bulk of the samples analyzed, but failed on the high end of the statistical distribution for TSP, leading to over-predictions of the highest and second highest concentrations, which are the focus of many air quality regulations for short-term particulate concentrations. The FDM Model is judged to be superior to the ISC Model in predicting the impacts from fugitive dust sources for the data evaluated in this study.

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Fugitive Dust Model (FDM)
Second Validation Study

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April, 1990

Table of Contents

1.0 Introduction .... A(2)-1

2.0 Methodology and Model Inputs .... A(2)-3

3.0 Air Quality Modeling Results .... A(2)-13

4.0 Conclusions .... A(2)-43

References .... A(2)-45

1.0 Introduction

The Fugitive Dust Model (FDM) was developed as an alternative to the previously recommended Industrial Source Complex Model (ISC) for the purposes of computing fugitive dust impacts. An initial validation study was performed using measured air quality and meteorological data from a western surface mining operation. The results of the first validation study were encouraging, but the number of data points was limited. A second data base was identified for the purpose of conducting an additional validation study for the FDM. The second data base differed in several important ways from the first data base. The first data base was collected for the purposes of determining compliance with air quality concentration regulations. As such, it was collected at locations which were predominantly at property boundary locations. Since the surface mine examined in the first validation study had considerable buffer space between the actual sources of dust and the property boundary, the source receptor distances were on the order of 500 meters or more.

The data base for the current (second validation) study was collected for research purposes, not for compliance purposes. As a result, the monitoring locations were very close to the sources -- in many cases less than 100 meters away. The reported concentrations were much higher. The second validation data set was collected at an eastern surface mining operation which also posed some unanswered questions. Emission rates for both the first and second validation studies were based on emission factors which had been developed at western surface mining operations, and the applicability to the higher humidity and other different meteorology of the eastern setting was a major uncertainty of the study.

The purpose of the current document is to detail the second validation study. Like the first validation study, reported by TRC in the FDM User's Guide, (April, 1990)[1]; TSP, PM-10, and meteorological measurements were available at several locations; in addition an extensive record of mining information was used to generate a daily fugitive emissions inventory. Daily emissions were modeled for 120 days during the late summer and fall of 1985 and were compared with TSP and PM-10 monitoring data using the statistical techniques recommended by EPA (Cox et. al., 1988)[2]. Statistical approaches have historically been used to evaluate model performance in comparing preferred regulatory dispersion models with non-regulatory modeling approaches. Preferred regulatory models are listed in EPA's Guideline on Air Quality Models (EPA-450/2-78-027R, including Supplement A, July 1987). This analysis demonstrates that FDM is superior to the EPA ISCST Model (EPA-450/4-88-002) for modeling fugitive dust sources.

2.0 Methodology and Model Inputs

The key to any model comparison evaluation study is a well designed ambient and meteorological monitoring study coupled to a high quality emissions inventory. This evaluation was possible because following data were available:

> Daily TSP and PM-10 measurements were made at five locations throughout the mining complex. The measurement sites were located to provide good indications of impacts of mining, loading and materials transport activities.
>
> Detailed site activity information was available to quantify emissions from the variety of sources located at the mine. A high quality, daily emissions inventory was generated for model input.
>
> On site meteorological data were available to define hourly fugitive emissions transport. The data consisted of wind speed and direction, sigma theta, ambient temperature and local rainfall.

Figure 1 depicts the locations of the five ambient monitoring sites and all fugitive dust sources as defined for ISCST input. Both ISC and FDM can treat area sources (although they use a different method), but one of the major differences between FDM and ISC is that FDM treats line sources directly, instead of treating them as a series of "volume" sources as shown in the figure. The volume sources are very similar to point sources, except the point has an initial horizontal dimension and an initial vertical dimension. The initial horizontal dimension is shown as the diameter of the circles in Figure 1. The initial horizontal dimension is input to the model as the initial value for the standard deviation of the concentration in the crosswind dimension, labeled sigma-y zero (σ_{y0}). The initial vertical dimension is similarly input to the model as the initial standard deviation of the concentration in the vertical, labeled sigma-z zero (σ_{z0}). The size of the area sources, as depicted, are approximately those of the input sources. The volume sources (coal and overburden haul roads) are depicted in the figure, although all are defined with a σ_{y0} of 58.0 meters and a σ_{z0} as 2.14 meters. Line sources were used to define haul roads for the FDM modeling analysis.

The surface mining operation is located in mildly rolling terrain typical of the mid-west and east. The mining company provided on-site activity data including daily overburden and coal removal quantities from active mining locations. The mine included 21 active coal removal locations of various area dimensions. The 21 coal removal sites were segmented into 63 square area sources as required by the ISCST model. Since ISCST does not calculate impacts for line sources, all haul roads were modeled as volume sources. Overburden haul roads were segmented into 85 volume sources and coal haul roads

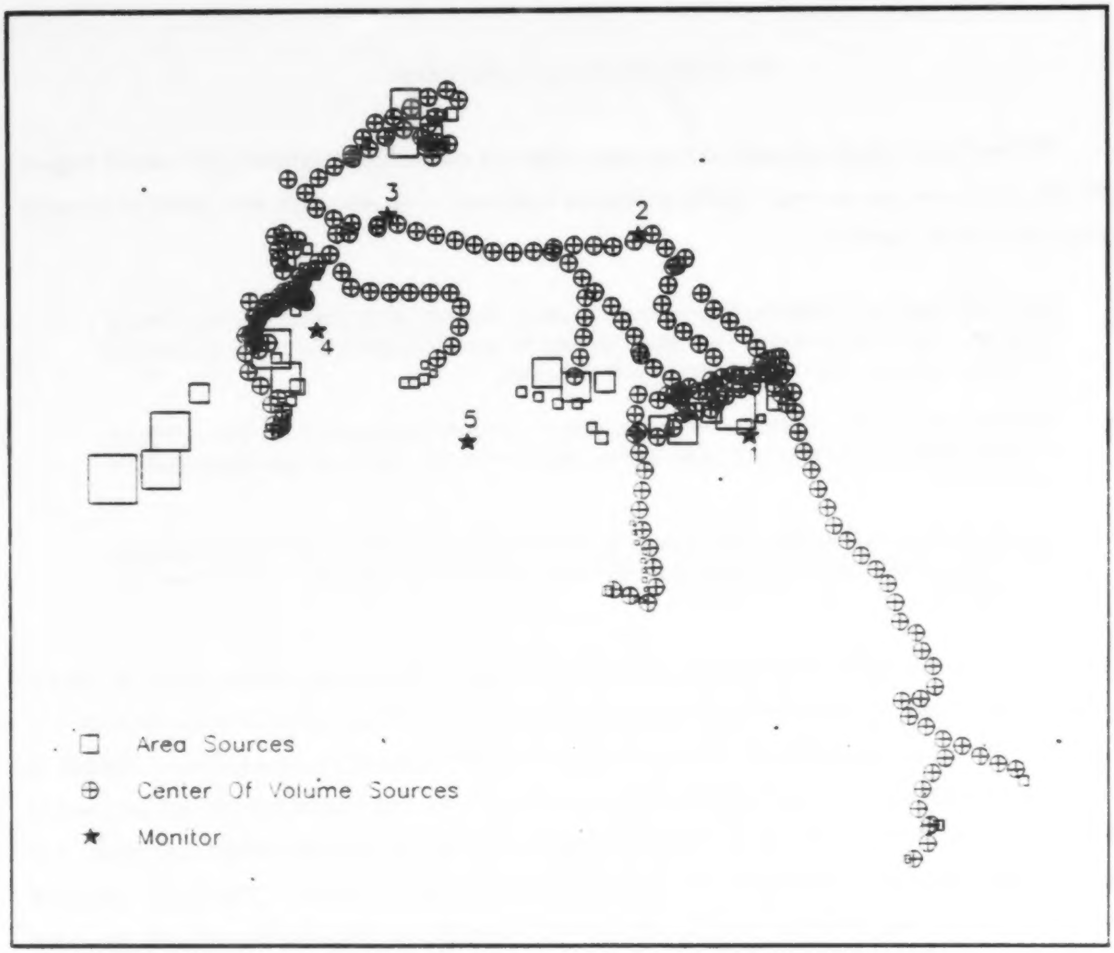

Figure 1. Source and Receptor Locations in the ISC Model

into 152 volume sources. The mine activity records provided by the company indicated which excavation areas were active on a given day and the corresponding haul roads utilized for coal and overburden removal. Model performance for each day was evaluated using the most representative source emissions.

The FDM model was designed to model fugitive dust from mining activities defined as area sources and dirt roadways using the line source algorithm in CALINE3[3]. The 153 coal haul road volume sources input to ISCST were represented as 47 line segments carefully located to represent actual road locations. The 85 overburden haul roads were represented by 21 line sources. All area sources were input to FDM as defined for ISCST. Unlike ISCST, FDM can accept rectangularly-shaped area sources whose sides can be at any angle to the X-Y axis. However, the comparison study was performed with emphasis placed on the treatment of fugitive dust line sources and all area sources were defined equivalently in both models.

Total fugitive emissions for August to December, 1985 are listed in Table 2-1. The tonnage of TSP generated by each activity was based on total coal and overburden removal and emissions factors reported in the EPA compilation of emissions factors AP-42. The emission estimates were derived using the parameters specified in Table 2-2. Table 2-1 indicates that over half of the emissions are associated with access and haul roads.

Two sets of input data for each model were generated for each modeling day, a TSP and a PM-10 input set. The particle size distribution for the TSP data sets were segregated into particle characteristics as shown in Table 2-3.

The particle size distribution was derived from a universal distribution characteristic of western mining (PEDCo and TRC, 1982)[4]. All values were calculated using the techniques specified in the user's guide for ISCST[5]. PM-10 input files utilized only that portion of the input set specific to PM-10.

Virtually all of the emission factors used to estimate the fugitive dust emission rates were taken from the EPA's Compilation of Fugitive Dust Emission Factors, Document No. AP-42. The emission factor document does not provide PM-10 fractions for all fugitive dust emission rates. Emissions estimates for blasting, truck loading, dozing, dragging, scrapers (travel mode), grading, light and medium vehicle traffic and haul trucks are specified as PM-15 sized particles. Therefore, PM-10 emissions for these activities were estimated from the western mining studies mentioned above assuming that mass fractions of particles less than 15 microns from the universal particle distribution matched those at the site. PM-10 emissions were calculated from PM-15 emissions by multiplying by 0.646.

Fugitive dust from haul roads, overburden haulback and light and medium duty vehicle traffic was controlled by water spraying. Control efficiencies can vary between 0.0 percent for no watering to 55 percent for twice per hour watering. Control efficiencies at the mine varied from 21.7 percent in August to 4.8 percent in December based on watering records provided by the mining company. Roadway watering was discontinued in the later part of the study period as natural precipitation levels increased and dropping ambient temperatures made roadway watering less desirable.

Two template input data sets, one using the ISCST format and the second using the FDM format, were developed including all sources emissions possible from the mine. A FORTRAN program was written to integrate the mine activity data and define the source emissions that would occur for each day of monitoring data. The FORTRAN code produces an FDM and an ISCST input data set for TSP and for PM-10 for each day. The code also extracts the 24 hours of meteorological data for that particular day to be included in the input data sets.

A background value was added to each value of TSP and PM-10 predicted by ISCST and FDM. Background was chosen as the lowest measured value from the five monitors (usually monitoring site #5).

Table 2-1: Total TSP Mine Emissions; August - December, 1985

	ACTIVITY	TSP (TONS)	PERCENT OF TOTAL
1.	TOPSOIL REMOVAL	17.16	1.5
2.	SCRAPER TRAVEL: TOPSOIL	N/A	N/A
3 .	TOPSOIL REPLACEMENT	12.45	1.1
4.	OVERBURDEN DRILLING	9.60	0.8
5.	OVERBURDEN BASTING	8.42	0.7
6a.	OVERBURDEN REMOVAL: DRAGLINE	313.10	27.7
6b.	OVERBURDEN REMOVAL: TRUCK/SHOVEL	0.15	0.01
6c.	OVERBURDEN REMOVAL: "B" MACHINE	0.03	NEGLIGIBLE
6d.	OVERBURDEN REMOVAL: SCRAPER/DOZER	7.84	0.7
7.	HAUL TRUCK TRAVEL: OVERBURDEN	89.63	7.6
8.	OVERBURDEN SHAPING: DOZERS	8.64	0.8
9.	COAL LOADING INTO HAUL TRUCKS	30.80	2.7
10.	HAUL TRUCK TRAVEL: COAL	378.49	33.4
11.	COAL DUMP	0.01	NEGLIGIBLE
12.	COAL PILE MAINTENANCE: DOZERS	3.86	0.3
13.	WIND EROSION	23.63	2.1
14.	LT DUTY VEHICLE/ACCESS ROADS	210.85	18.6
15.	ROAD MAINTENANCE: GRADERS	20.59	1.8
16.	CRUSH, SCREEN, CONVEYING	0.74	0.1
17.	COAL LOADOUT	0.03	NEGLIGIBLE
18.	AUGER	N/A	N/A
	TOTAL EMISSIONS:	1,132.02	

Source: TRC Environmental Consultants, Inc.

Table 2-2: Input Parameters Used To Estimate Emissions

MINING OPERATION	DESCRIPTION	AP-42 INPUT VALUES
Overburden blasting	**area blasted (A)**	**3,113 m^2/blast**
Overburden removal dragline	**drop distance (d)**	**20.0 ft**
	moisture (M)	**16.8%**
Dozers-overburden	**silt content (s)**	**6.9%**
	moisture (M)	**16.8%**
Coal loading	**moisture (M)**	**15.0%**
Haul truck: coal	no. of wheels (w)	10.0
	silt loading (L)	9.1 g/m^2
Haul truck: overburden	no. of wheels (w)	6.0
	silt loading (L)	9.1 g/m^2
Coal dump	silt content (s)	6.0%
	wind speed (U)	5.46 mph
	drop height (d)	5.0 ft
	moisture (M)	15.0%
	dump capacity (Y)	50.0 yd^3
Dozers coal	silt content (s)	6.0%
	moisture (M)	15.0%
Light- and medium-duty vehicle	moisture (M)	1.7%
Graders	speed (S)	7.1 mph
Coal loadout	silt content (s)	6.0%
	wind speed (U)	8.9 mph
	drop height (d)	5.0 ft
	moisture (M)	15.0%

Source: TRC Environmental Consultants, Inc.

Table 2-3. Particle Characteristics Used in the Model Runs

DIAMETER RANGE (microns)	MASS FRACTION	ISCST SETTLING VELOCITY (m/sec)	ISCST REFLECTION COEFFICIENT
0 - 10	0.270	0.00074	0.93
10 - 20	0.263	0.00669	0.80
20 - 30	0.467	0.01859	0.72

Note: For FDM, the settling velocities are computed by the model, and a second particle characteristic, the deposition velocity, is also computed by the model on an hour by hour basis. The reflection coefficient is used only by ISC.

Both the FDM and ISCST models require hourly values for wind speed, wind direction, temperature, atmospheric stability and mixing height. Wind speed, wind direction and temperature are measured directly by the sensors at monitor #1. Atmospheric stability is a measure of the turbulent mixing capacity of the atmosphere and was estimated from the standard deviation of the wind direction and from the wind speed and time of day. Stability is expressed as one of 6 classes labeled A through F, where A is the least stable (greatest turbulent mixing) and F is the most stable (least turbulent mixing). The conversion from standard deviation of the wind direction, wind speed and time of day to stability is accomplished as shown in Table 2-4 (taken from EPA, 1987)[6].

For fugitive dust impacts, results are generally very insensitive to values used for mixing height because the emissions are released at or near the ground, and the impacts are generally very close to the source. As a result the emissions have little opportunity to mix vertically to the height of the mixing layer. To provide the models with the required values, a mixing height of 500.0 meters was assigned for all hourly periods. Figure 2 is a frequency distribution of hourly meteorological data used for the model comparison study.

Table 2-4. Estimation of Stability Class

Initial Estimate of Stability Class is provided by:

Standard Deviation	Stability Class
> 22.5	A
17.5 - 22.5	B
12.5 - 17.5	C
7.5 - 12.5	D
3.75 - 7.5	E
< 3.75	F

Stability Classes are Adjusted by time of day and wind speed by:

Time of Day	Initial Stability	Wind Speed (m/sec) Stability	Final
Daytime	A	$U < 3$	A
		$3 \le U < 4$	B
		$4 \le U < 6$	C
		$6 \le U$	D
	B	$U < 4$	B
		$4 \le U < 6$	C
		$6 \le U$	D
	C	$U < 6$	C
		$6 \le U$	D
	D, E or F	Any	D
Nighttime	A	$U < 2.9$	F
		$2.9 \le U < 3.6$	E
		$3.6 \le U$	D
	B	$U < 2.4$	F
		$2.4 \le U < 3.0$	E
		$3.0 \le U$	D
	C	$U < 2.4$	E
		$2.4 \le U$	D
	D	Any	D
	E	$U < 5.0$	E
		$5.0 \le U$	D
	F	$U < 3.0$	F
		$3.0 \le U < 5.0$	E
		$5.0 \le U$	D

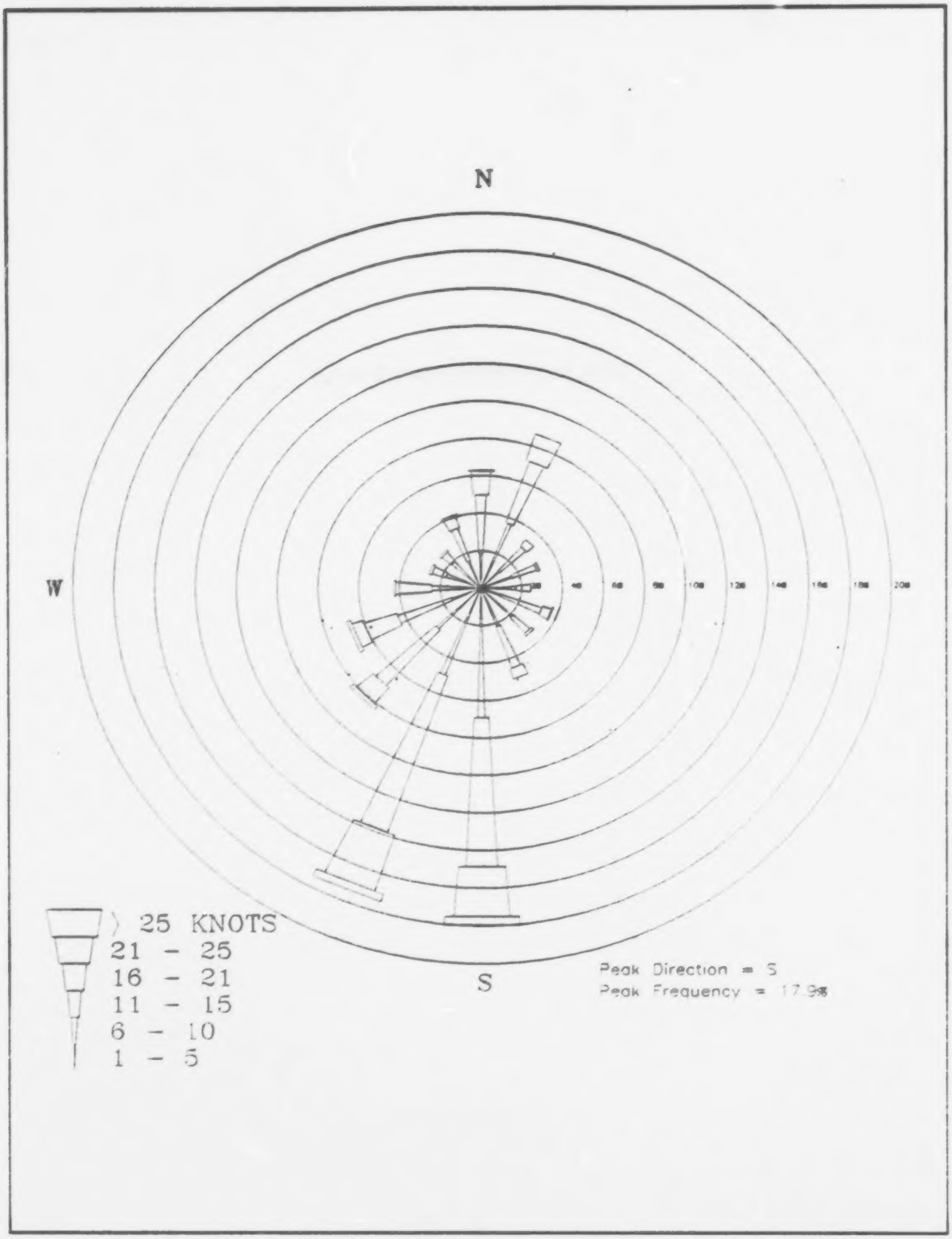

Figure 2. August 3 - December 23, 1985

3.0 AIR QUALITY MODELING RESULTS

The FDM and ISCST models were run for the 120 case days identified earlier, and the concentrations, both PM-10 and TSP, were computed as the sum of the modeled concentration and the background. There are a number of ways of comparing the model predictions with the measured data. The methods can generally be separated into two distinct classes of comparison: paired and unpaired comparisons. In paired data comparisons, a model's prediction at a particular receptor, for a particular period of time is compared to the measured values at that same location and time. In unpaired comparisons, a group of model predictions are analyzed to determine their own statistical properties. The measured data are similarly analyzed, and the results of the statistical evaluations are compared.

In one sense, the model's true evaluation is based on its ability to predict actual measured concentrations, and only paired data comparisons are indicative of this ability. However, consideration must be given to how the model is used in a regulatory setting. The models are used to predict compliance or non-compliance with regulatory criteria. It is not always relevant that they predict the location or time period of a particular concentration, but rather that they generally be reliable at predicting the levels at which a project is regulated (e.g. a maximum 24-hour particulate concentration at any property boundary location).

For the current analysis, both paired and unpaired data comparisons have been conducted and will be presented. Actually, three classes of comparisons have been performed:

- first, the data are paired in time and space,
- second, the data are paired in space, but not in time, and
- finally, the data are completely unpaired.

For the paired data, the comparison is presented in two formats. First, the measured versus predicted values are shown in Tables 3-1 through 3-5 for the TSP comparisons for sites 1 through 5 respectively, and in Table 3-6 through 3-10 for PM-10 for sites 1 through 5 respectively. Second, a "scatter plot" of the measured and predicted values for these same four cases are shown in Figures 3-1 through 3-4.

The tables and figures do not show the dramatic illustration of the over-prediction tendency of ISC as compared with FDM that the first validation study had indicated. However, the same tendencies are present in the data comparisons. Both the TSP and PM-10 figures show ISC has a greater tendency to predict above the diagonal line of perfect prediction in the figure, while the FDM predictions are more centered on the diagonal.

One means of comparison is to determine what number of the data points are within a factor of

Table 3-1. Model Results Comparison for TSP at Site 1

Julian Day No.	Measured Concen. (ug/m3)	FDM Predicted Concen. (ug/m3)	ISCST Predicted Concen. (ug/m3)
215	81.0	43.0	43.0
216	69.0	33.0	33.0
217	143.0	50.0	50.0
218	46.0	43.0	43.0
219	38.0	38.0	38.0
220	37.0	38.2	37.9
221	187.0	194.2	214.6
222	84.0	92.6	159.6
223	118.0	84.4	100.0
224	60.0	63.8	64.8
225	78.0	78.0	78.0
226			
227			
228	44.0	62.7	99.2
229	67.0	41.0	41.0
230	42.0	42.5	48.9
231	148.0	89.0	115.2
232	87.0	154.7	269.0
233	231.0	163.3	275.6
234	110.0	146.7	270.4
235			
236	41.0	41.0	41.0
237	25.0	25.0	25.0
238	25.0	25.2	25.8
239	50.0	43.0	43.0
240	70.0	76.4	92.1
241	89.0	82.3	88.7
242			
243	59.0	51.8	63.5
244	35.0	40.9	46.9
245	61.0	61.0	61.0
246	54.0	54.0	54.0
247	66.0	66.0	66.0
248	48.0	48.0	48.0
249	50.0	50.0	50.0
250	45.0	45.0	45.0
251	81.0	65.0	65.0
252	142.0	78.3	80.2
253	127.0	92.1	99.9
254	189.0	193.9	352.5
255	96.0	131.1	293.4
256	110.0	71.2	144.0
257	57.0	66.3	82.1
258	81.0	59.0	62.6
259	198.0	103.3	166.6
260	79.0	64.0	64.0
261	77.0	73.7	149.0
262			
263			
264	82.0	105.0	162.3
265			
266	85.0	77.0	77.0
267	87.0	55.3	83.9
268	62.0	123.0	224.9
269	31.0	39.0	54.7
270	136.0	156.8	353.5
271	39.0	32.0	32.0
272	32.0	32.0	32.0
273	54.0	42.0	42.0
274	42.0	51.1	91.3
275	261.0	60.1	76.3
276	84.0	60.8	71.4
278	30.0	26.0	26.0
284	112.0	167.5	300.7
285	56.0	56.0	56.0
289	178.0	92.1	132.3
290	45.0	62.5	82.7
291	53.0	43.0	43.0
292	42.0	30.0	30.0
293			
294	15.0	24.9	28.5
295	28.0	43.0	58.9
296	16.0	17.4	19.6
297	21.0	18.0	18.0
298	91.0	264.6	500.3
299	25.0	25.0	25.0
300	100.0	95.3	113.1
301	223.0	54.2	62.6
302			
303	81.0	69.8	154.8
304	44.0	47.6	50.6
305	31.0	36.7	43.3
306	9.0	9.0	9.0
307	7.0	6.0	6.0
308	29.0	57.0	125.6
309	68.0	88.8	151.8
310	26.0	20.6	27.3
311	19.0	16.0	16.0
312	22.0	21.0	21.0
314	35.0	29.8	31.1
315	59.0	72.3	126.3
316	22.0	27.4	28.6
317	26.0	26.0	26.0
322			
323	24.0	24.0	24.1
324	29.0	22.9	25.7
325	70.0	64.4	85.8
326	35.0	45.8	57.9
327	32.0	32.7	34.1
328	38.0	39.2	41.9
329	30.0	37.9	49.8
330	26.0	32.2	46.8
331	16.0	14.2	19.2
332	12.0	11.6	16.1
333	21.0	18.3	18.5
334	33.0	29.1	31.0
335	14.0	12.0	12.0
336	32.0	31.0	31.0
337	38.0	30.6	31.3
338	41.0	38.0	38.0
339	30.0	30.0	30.0
340	42.0	26.7	26.5
341			
342	33.0	29.0	29.0
343			
344	42.0	42.0	42.0
345	42.0	35.0	35.0
346	59.0	71.3	145.5

Table 3-2. Model Results Comparison for TSP at Site 2

Julian Day No.	Measured Concen. (ug/m3)	FDM Predicted Concen. (ug/m3)	ISCST Predicted Concen. (ug/m3)
215			
216	232.0	69.8	92.0
217			
218	243.0	400.0	423.5
219			
220	214.0	117.6	305.2
221			
222	197.0	97.5	103.0
223			
224	840.0	487.0	360.5
225			
226	240.0	329.2	377.3
227	125.0	618.3	491.5
228	39.0	123.8	165.3
229	88.0	57.7	67.7
230	80.0	49.4	106.8
231	185.0	145.9	280.5
232	187.0	181.8	150.3
233	92.0	77.1	103.6
234	570.0	308.6	476.4
235	651.0	1230.5	1276.3
236	147.0	45.5	59.6
237	127.0	37.7	103.8
238	755.0	294.2	233.0
239	227.0	134.9	95.1
240	113.0	105.7	194.1
241	598.0	277.1	535.7
242	89.0	210.5	258.3
243	37.0	36.3	42.4
244	56.0	64.3	79.0
245	94.0	61.3	61.0
246	367.0	438.1	402.9
247	194.0	591.6	200.5
248	194.0	513.8	775.7
249	178.0	607.5	333.0
250	81.0	52.1	60.5
251	94.0	69.9	77.2
252	207.0	417.9	349.7
253	93.0	208.1	332.8
254	73.0	71.0	71.0
255	63.0	63.0	63.0
256	90.0	36.0	36.0
257	79.0	56.0	56.2
258	131.0	60.3	71.3
259	439.0	81.9	91.0
260	693.0	294.7	330.2
261	473.0	512.4	671.8
262	481.0	785.9	1270.7
263	323.0	416.4	591.4
264	182.0	135.4	147.0
265	220.0	70.7	72.3
266	473.0	481.7	325.2
267	193.0	299.4	236.7
268	164.0	125.8	147.8
269	69.0	65.0	117.5
270	36.0	54.8	86.2
271	117.0	86.2	95.5
272	112.0	41.6	72.9
273	251.0	102.8	227.8
274	28.0	78.7	178.7
275	41.0	61.6	113.5
276	210.0	107.7	262.8
278	31.0	59.7	39.6
284	79.0	125.7	118.4
285	75.0	57.4	60.7
289	70.0	401.0	227.2
290	636.0	96.4	73.8
291	165.0	67.8	100.3
292	58.0	81.1	43.5
293	16.0	16.0	16.4
294	21.0	15.0	15.0
295	28.0	31.3	44.3
296	201.0	27.8	50.4
297	35.0	53.5	88.8
298	43.0	49.4	58.1
299	106.0	64.8	95.8
300	71.0	122.9	134.7
301	43.0	35.0	35.0
302			
303	170.0	200.4	248.4
304	71.0	36.0	36.0
305	99.0	111.5	70.6
306	14.0	9.1	9.0
307	11.0	6.0	6.0
308	10.0	13.3	20.0
309	4.0	4.2	4.0
310	16.0	74.1	138.8
311	22.0	233.3	208.2
312	25.0	24.6	29.4
314	21.0	85.8	102.3
315	35.0	61.9	55.4
316	31.0	222.0	306.9
317	35.0	116.0	75.8
322	29.0	705.4	411.6
323	180.0	534.6	507.6
324	64.0	246.5	176.5
325	67.0	44.6	46.1
326	81.0	52.3	72.8
327	44.0	37.2	52.1
328	39.0	46.5	49.1
329	34.0	24.4	24.8
330	33.0	72.0	104.1
331	13.0	11.3	11.9
332	10.0	11.8	16.1
333	23.0	18.3	19.0
334	30.0	34.0	31.6
335	13.0	13.6	14.1
336	138.0	31.6	31.1
337	256.0	35.4	42.8
338	472.0	39.2	40.3
339	534.0	32.9	38.2
340	43.0	89.2	185.8
341	42.0	118.0	117.7
342	34.0	247.7	256.6
343	64.0	295.4	379.8
344	57.0	70.7	106.5
345	35.0	57.9	89.4
346	23.0	49.2	100.4

Table 3-3. Model Results Comparison for TSP at Site 3

Julian Day No.	Measured Concen. (ug/m3)	FDM Predicted Concen. (ug/m3)	ISCST Predicted Concen. (ug/m3)
215			
216			
217			
218			
219			
220			
221			
222			
223	108.0	74.9	75.7
224			
225	578.0	967.9	1185.0
226	227.0	590.6	713.3
227	222.0	1269.5	831.9
228	105.0	567.8	191.8
229	102.0	54.7	66.0
230	66.0	105.4	163.4
231	416.0	294.6	542.8
232	211.0	359.1	305.4
233	160.0	104.0	159.7
234	687.0	459.6	737.7
235	732.0	1258.5	1866.2
236	65.0	169.3	226.4
237	110.0	249.7	446.9
238	543.0	382.0	476.9
239	612.0	492.4	734.1
240	445.0	753.2	1289.3
241	774.0	880.8	2354.6
242	118.0	432.4	530.7
243	88.0	37.9	46.4
244	60.0	67.6	103.3
245	141.0	83.7	114.0
246	462.0	514.5	726.5
247	665.0	839.6	605.3
248	295.0	1027.0	1432.0
249	633.0	862.9	606.5
250	191.0	295.3	490.7
251	214.0	267.6	433.8
252	456.0	567.2	628.2
253	319.0	435.1	605.5
254	120.0	71.7	72.4
255			
256			
257	155.0	66.4	87.6
258	169.0	146.7	125.8
259	1344.0	254.3	391.8
260	785.0	1529.1	3195.8
261	1014.0	682.4	1371.7
262	750.0	693.4	1577.8
263	1036.0	482.1	1018.7
264			
265	718.0	230.1	262.3
266	602.0	432.6	436.9
267	1077.0	541.9	510.9
268	267.0	255.2	373.3
269	183.0	545.2	1011.4
270	230.0	190.5	310.6
271	254.0	99.2	160.8
272	245.0	276.7	572.6
273	874.0	942.7	2117.0
274	84.0	661.9	640.9
275	229.0	243.7	330.4
276	231.0	1024.2	2400.9
278			
284	241.0	111.0	110.6
285	135.0	129.9	188.6
289	430.0	584.5	621.7
290	310.0	384.3	370.6
291	273.0	418.6	850.6
292	164.0	98.1	103.1
293	20.0	23.0	28.8
294	15.0	118.6	127.2
295	50.0	353.7	518.1
296	93.0	492.8	560.8
297	116.0	691.7	1188.6
298	450.0	137.0	92.3
299	138.0	66.7	121.4
300	75.0	122.2	152.5
301	58.0	40.1	42.3
302			
303			
304	36.0	50.4	69.5
305	42.0	234.1	129.5
306	31.0	264.8	194.5
307	6.0	528.4	391.3
308	13.0	14.0	32.5
309	5.0	4.0	4.0
310	38.0	644.9	598.1
311	34.0	498.6	580.3
312	32.0	186.6	306.5
314	51.0	84.5	129.9
315	28.0	80.6	133.0
316	33.0	360.7	820.2
317	81.0	274.0	312.7
322			
323	190.0	519.0	877.2
324	112.0	311.4	232.3
325	62.0	74.6	94.4
326	80.0	327.1	356.7
327	55.0	95.3	85.6
328			
329	37.0	75.9	134.0
330	41.0	592.9	559.9
331			
332			
333	20.0	24.0	31.3
334	31.0	39.3	46.0
335	47.0	162.2	169.1
336	360.0	99.1	164.2
337	673.0	156.9	357.0
338	558.0	480.8	1137.2
339	189.0	160.3	263.4
340	46.0	345.8	791.5
341	45.0	257.7	325.2
342	38.0	244.2	393.2
343	109.0	398.2	796.7
344	89.0	639.2	1139.6
345	67.0	438.3	726.9
346	22.0	201.1	561.6

Table 3-4. Model Results Comparison for TSP at Site 4

Julian Day No.	Measured Concen. (ug/m3)	FDM Predicted Concen. (ug/m3)	ISCST Predicted Concen. (ug/m3)	Julian Day No.	Measured Concen. (ug/m3)	FDM Predicted Concen. (ug/m3)	ISCST Predicted Concen. (ug/m3)
215	43.0	55.6	44.5	274	188.0	181.2	649.7
216				275	63.0	187.4	463.2
217	50.0	56.0	63.0	276	222.0	140.4	342.8
218				278			
219	66.0	91.7	807.3	284	222.0	154.4	287.5
220				285	193.0	75.6	99.0
221	190.0	258.7	1070.7	289	271.0	285.6	439.1
222				290	159.0	133.1	338.3
223	66.0	141.0	695.1	291	176.0	163.7	238.5
224				292	344.0	281.5	432.9
225	212.0	179.1	770.4	293	33.0	21.8	29.3
226	146.0	170.2	532.5	294	37.0	96.5	229.5
227	128.0	284.9	1432.7	295	37.0	134.3	423.8
228	60.0	281.0	3501.7	296	48.0	48.4	103.4
229	41.0	42.5	43.2	297	51.0	32.0	18.0
230	38.0	149.0	456.2	298	253.0	303.6	362.9
231	257.0	807.5	3003.9	299	59.0	32.9	35.8
232				300			
233	137.0	163.6	289.4	301			
234	365.0	246.9	283.0	302	64.0	260.7	591.5
235	128.0	122.8	154.3	303	32.0	348.4	666.4
236	87.0	41.6	41.6	304	51.0	108.6	179.6
237	27.0	30.7	25.0	305			
238	160.0	106.8	43.8	306	17.0	9.7	9.7
239	419.0	728.2	4218.7	307	6.0	7.7	11.3
240	650.0	683.2	3737.6	308	32.0	149.3	263.6
241	438.0	333.3	739.6	309	16.0	410.0	868.8
242	262.0	265.9	484.1	310	25.0	24.6	26.4
243	54.0	139.7	179.1	311	16.0	16.2	16.5
244	177.0	55.5	47.2	312	33.0	45.5	21.0
245	311.0	134.7	100.7	314	30.0	71.9	38.9
246	704.0	115.8	124.1	315	28.0	140.9	101.5
247	604.0	185.7	172.4	316	29.0	41.7	36.1
248	712.0	82.2	73.8	317	34.0	73.6	26.0
249	398.0	132.2	83.5	322			
250	204.0	119.3	45.0	323	37.0	45.6	59.8
251	151.0	129.2	65.0	324	150.0	46.7	55.0
252	757.0	222.8	162.8	325	69.0	95.7	142.2
253	617.0	288.1	932.6	326	136.0	69.1	113.8
254	169.0	504.9	1126.0	327	84.0	128.7	204.9
255				328	39.0	56.1	62.3
256	159.0	78.5	226.3	329	29.0	51.1	84.9
257	56.0	75.2	89.8	330	35.0	134.0	161.9
258	128.0	98.5	228.3	331	27.0	65.5	108.3
259	290.0	129.1	301.9	332	11.0	11.5	12.3
260	700.0	150.1	243.9	333	18.0	22.1	28.4
261	525.0	163.3	251.7	334	28.0	52.4	79.5
262	609.0	135.3	142.1	335	17.0	22.1	18.6
263	836.0	203.5	426.4	336	77.0	156.8	86.9
264	628.0	198.4	378.7	337	119.0	277.5	207.1
265	271.0	110.2	161.7	338	46.0	45.7	65.2
266	407.0	117.4	137.7	339			
267	132.0	107.9	235.0	340	151.0	572.2	679.2
268	130.0	179.7	482.2	341	49.0	141.8	65.4
269	125.0	281.5	799.8	342	35.0	45.4	29.0
270	183.0	200.2	327.3	343	145.0	195.1	290.4
271	187.0	261.4	732.0	344	65.0	65.2	69.1
272	123.0	101.1	121.1	345	58.0	64.7	35.2
273	202.0	130.1	163.9	346	219.0	623.9	807.5

Table 3-5. Model Results Comparison for TSP at Site 5

Julian Day No.	Measured Concen. (ug/m3)	FDM Predicted Concen. (ug/m3)	ISCST Predicted Concen. (ug/m3)
215			
216	33.0	33.0	33.0
217			
218	43.0	43.0	43.0
219			
220	82.0	38.5	38.7
221			
222	76.0	76.5	78.1
223			
224	62.0	72.6	94.1
225			
226	86.0	92.6	119.3
227	54.0	54.0	54.0
228	31.0	46.9	99.7
229	44.0	44.8	56.4
230	52.0	41.3	49.2
231	63.0	79.8	102.0
232			
233	77.0	94.6	131.0
234	74.0	102.1	174.8
235	74.0	79.6	99.4
236	48.0	41.0	41.0
237	27.0	25.0	25.0
238	38.0	25.0	25.0
239	43.0	43.0	43.0
240	109.0	70.1	70.2
241	80.0	80.0	80.0
242	59.0	67.1	82.4
243	34.0	41.4	62.7
244	40.0	36.0	38.0
245	69.0	61.0	61.0
246	61.0	54.0	54.0
247	68.0	66.0	66.0
248	62.0	48.0	48.0
249	55.0	50.0	50.0
250	55.0	45.0	45.0
251	65.0	65.0	65.0
252	76.0	79.5	83.4
253	87.0	106.0	134.7
254	71.0	102.1	146.5
255	64.0	90.4	142.5
256	36.0	84.3	195.4
257	64.0	57.8	61.8
258	56.0	62.8	82.2
259	77.0	82.4	98.0
260	64.0	64.0	64.0
261	60.0	67.3	99.1
262	93.0	101.5	131.2
263	94.0	96.5	100.0
264	92.0	82.1	82.0
265	69.0	77.1	109.3
266	77.0	77.0	77.0
267	27.0	29.7	32.0
268	104.0	87.1	143.4
269	31.0	35.1	43.6
270	46.0	118.3	327.9
271	32.0	32.0	32.0
272	39.0	32.8	32.5
273	42.0	42.0	42.0
274	17.0	43.1	80.5
275	48.0	66.4	130.6
276	49.0	73.4	127.3
278	26.0	26.0	26.0
284	73.0	99.8	146.5
285			
289	63.0	78.3	101.5
290	42.0	51.8	77.3
291	43.0	43.0	43.0
292	30.0	30.0	30.0
293	19.0	18.1	20.0
294	23.0	37.8	88.5
295	28.0	52.7	124.0
296	21.0	27.7	49.5
297	18.0	18.0	18.0
298	41.0	72.2	121.9
299	30.0	26.7	28.5
300			
301	35.0	54.9	85.6
302	112.0	81.4	122.6
303	29.0	47.8	90.1
304			
305	25.0	31.6	35.0
306	9.0	9.0	9.0
307	7.0	6.0	6.0
308	13.0	23.3	39.4
309	11.0	43.5	78.7
310	17.0	16.4	16.5
311	17.0	16.0	16.0
312	21.0	21.0	21.0
314	21.0	25.4	37.5
315	26.0	32.5	46.3
316	24.0	22.9	24.5
317	27.0	26.0	26.0
322			
323	27.0	24.0	24.0
324	22.0	22.1	22.0
325	44.0	57.3	75.8
326	32.0	36.2	43.0
327	120.0	32.1	32.1
328	41.0	43.3	57.7
329	24.0	26.5	29.7
330	25.0	25.1	25.0
331	11.0	18.4	29.0
332			
333	19.0	20.4	25.3
334	32.0	29.0	30.3
335	12.0	12.0	12.0
336	31.0	31.0	31.0
337	30.0	30.4	30.5
338	38.0	39.7	53.6
339	38.0	30.0	30.0
340	26.0	26.0	26.0
341	36.0	36.0	36.0
342	29.0	29.0	29.0
343	48.0	53.7	66.3
344	46.0	44.5	50.9
345			
346	24.0	45.7	110.3

Table 3-6. Model Results Comparison for PM-10 at Site 1

Julian Day No.	Measured Concen. (ug/m3)	FDM Predicted Concen. (ug/m3)	ISCST Predicted Concen. (ug/m3)
215	37.0	36.0	36.0
216	32.0	25.0	25.0
217	42.0	36.0	36.0
218	36.0	34.0	34.0
219	31.0	31.0	31.0
220	32.0	29.5	29.4
221	62.0	67.5	76.2
222	67.0	70.6	78.6
223	52.0	56.0	54.9
224	34.0	34.9	34.9
225	60.0	60.0	60.0
226	70.0	63.1	67.0
227			
228	19.0	39.7	41.4
229	29.0	29.0	29.0
230	23.0	23.7	25.5
231	47.0	41.8	50.9
232	35.0	80.3	99.9
233	67.0	84.2	97.3
234	46.0	87.3	113.4
235			
236	35.0	35.0	35.0
237	21.0	20.0	20.0
238	39.0	27.2	27.4
239	30.0	28.0	28.0
240	39.0	39.2	44.0
241	70.0	60.5	62.3
242			
243	20.0	27.1	24.8
244	29.0	24.1	22.6
245	45.0	45.0	45.0
246	44.0	44.0	44.0
247	46.0	45.0	45.0
248	38.0	38.0	38.0
249	37.0	37.0	37.0
250	37.0	25.0	25.0
251	46.0	46.0	46.0
252	61.0	45.1	45.6
253	56.0	42.7	45.0
254	55.0	76.5	90.6
255	48.0	68.4	121.3
256	37.0	46.0	71.8
257	28.0	32.5	31.9
258	39.0	32.2	33.8
259	77.0	74.6	95.4
261	52.0	62.7	77.7
262			
263			
264	59.0	78.2	78.0
265			
266	60.0	45.0	45.0
267	16.0	24.9	28.4
268	29.0	65.8	102.4
269	20.0	24.8	30.5
270	38.0	89.3	121.0
271	24.0	24.0	24.0
272	31.0	31.0	31.0
273	47.0	40.0	40.0
274	11.0	27.5	28.0
275	102.0	33.5	36.5
276	39.0	37.6	39.9
278	16.0	14.0	14.0
285	38.0	38.0	38.0
289	43.0	45.3	54.5
290	21.0	33.8	38.5
291	41.0	41.0	41.0
292	31.0	24.0	24.0
293	16.0	13.5	13.4
294	11.0	16.1	16.6
295	15.0	25.2	28.9
296	12.0	12.9	13.5
297	16.0	16.0	16.0
298	27.0	120.9	139.7
299	14.0	14.0	14.0
300	36.0	43.6	41.2
301			
302			
303	29.0	43.0	78.3
304	24.0	27.7	28.0
305	13.0	17.5	20.5
306	7.0	6.0	6.0
307	5.0	3.0	3.0
308	13.0	29.4	46.9
309	9.0	39.1	51.5
310	11.0	13.4	15.2
311	16.0	13.0	13.0
312	15.0	13.0	13.0
314	19.0	23.6	21.6
315	22.0	38.7	36.3
316	17.0	19.8	19.8
317	24.0	22.0	22.0
322	18.0	18.0	18.0
323	21.0	21.0	21.0
324	16.0	14.7	15.3
325	33.0	31.6	36.7
326	21.0	28.3	31.6
327	26.0	26.6	27.0
328	30.0	30.8	31.2
329	20.0	23.4	27.6
330	21.0	24.0	28.5
331	12.0	8.4	10.3
332	6.0	7.2	7.6
333	16.0	15.2	15.2
334	25.0	25.8	26.1
335	10.0	10.0	10.0
336	12.0	12.0	12.0
337	17.0	16.4	16.5
338	26.0	24.0	24.0
339	21.0	21.0	21.0
340	28.0	23.4	23.2
341			
342	29.0	26.0	26.0
343	37.0	47.7	48.3
344	36.0	35.0	35.0
345	23.0	21.0	21.0
346	18.0	45.5	55.8

Table 3-7. Model Results Comparison for PM-10 at Site 2

Julian Day No.	Measured Concen. (ug/m3)	FDM Predicted Concen. (ug/m3)	ISCST Predicted Concen. (ug/m3)
215			
216	92.0	45.7	44.7
217			
218	83.0	168.1	189.7
219			
220	77.0	67.0	143.2
221			
222	105.0	66.7	66.0
223			
224	287.0	221.4	155.1
225			
226	87.0	164.0	183.8
227	58.0	289.1	227.2
228	19.0	65.7	78.2
229			
230	33.0	26.7	50.0
231	81.0	66.8	122.7
232	58.0	78.0	62.0
233	53.0	33.0	44.7
234	179.0	138.1	205.5
235	228.0	584.6	561.8
236	48.0	38.1	39.1
237	35.0	29.6	38.8
238	179.0	136.5	113.6
239	92.0	69.9	48.5
240	35.0	59.3	90.8
241	223.0	157.0	258.5
242	27.0	82.4	110.0
243	19.0	19.4	20.2
244	20.0	32.8	36.7
245	52.0	45.2	45.0
246	70.0	204.2	185.1
247	77.0	244.2	99.2
248	39.0	211.7	336.6
249	66.0	242.5	150.5
250	25.0	28.8	31.6
251	53.0	48.8	51.2
252	48.0	177.8	155.3
253	68.0	93.0	140.6
254	16.0	16.0	16.0
255	28.0	28.0	28.0
256	26.0	26.0	26.0
257	36.0	26.0	26.1
258	49.0	33.2	35.2
259	193.0	59.1	60.6
261	173.0	253.4	302.1
262	140.0	410.9	567.7
263	140.0	227.7	279.5
264	76.0	83.9	83.8
265	98.0	51.9	52.4
266	137.0	204.3	143.8
267	74.0	133.8	97.4
268	59.0	57.7	65.4
269	33.0	40.7	55.1
270	20.0	31.8	42.3
271	58.0	49.5	47.7
272	51.0	38.1	41.2
273	108.0	75.7	105.5
274	11.0	46.3	73.7
275	20.0	38.6	66.5
276	61.0	77.1	131.0
278	16.0	25.7	18.5
285	45.0	38.9	39.0
289	32.0	156.3	97.5
290	157.0	42.3	34.0
291	68.0	53.7	63.4
292	30.0	43.0	29.1
293	16.0	13.0	13.1
294	11.0	11.0	11.0
295	16.0	17.5	20.4
296	30.0	18.3	21.0
297	17.0	33.0	44.8
298	16.0	20.3	22.5
299	48.0	31.9	39.2
300	32.0	53.5	56.0
301	23.0	18.0	18.0
302			
303	46.0	114.2	121.6
304			
305	25.0	41.6	31.9
306	7.0	6.1	6.0
307	3.0	3.0	3.0
308	6.0	8.0	9.0
309	4.0	4.1	4.0
310	11.0	41.0	61.8
311	14.0	86.2	91.9
312	17.0	14.9	16.3
314	18.0	41.0	52.3
315	16.0	28.9	25.8
316	19.0	101.9	136.4
317	22.0	54.0	42.5
322			
323	56.0	194.2	217.9
324	23.0	97.2	78.1
325	22.0	21.4	21.9
326	33.0	31.0	37.3
327	26.0	29.6	34.3
328	35.0	34.3	33.6
329	17.0	17.3	17.3
330	23.0	43.2	53.1
331	7.0	7.1	7.4
332	9.0	7.2	7.7
333	15.0	15.1	15.2
334	28.0	28.1	26.3
335	10.0	10.6	10.9
336	60.0	12.3	12.0
337	50.0	19.2	19.8
338	112.0	24.7	25.0
339	82.0	22.9	24.3
340	32.0	60.1	88.1
341	29.0	60.6	63.2
342	34.0	104.6	121.4
343	35.0	137.4	172.1
344			
345	21.0	32.2	40.7
346	16.0	30.5	45.2

Table 3-8. Model Results Comparison for PM-10 at Site 3

Julian Day No.	Measured Concen. (ug/m3)	FDM Predicted Concen. (ug/m3)	ISCST Predicted Concen. (ug/m3)
215	58.0	41.5	47.9
216			
217	142.0	368.8	592.4
218			
219	56.0	183.7	101.7
220			
221	147.0	263.0	222.0
222			
223	50.0	52.2	49.7
224			
225	156.0	419.2	500.1
226	104.0	272.9	290.8
227	58.0	582.7	357.4
228	32.0	270.9	81.9
229	41.0	34.7	38.0
230	36.0	51.5	69.8
231	101.0	158.1	242.6
232	112.0	172.1	117.7
233	44.0	50.6	57.5
234	221.0	209.7	310.2
235	202.0	621.5	813.5
236	46.0	86.3	112.7
237	26.0	111.6	199.1
238	168.0	178.1	198.9
239	145.0	256.2	303.7
240	130.0	366.0	529.5
241	177.0	423.3	1022.6
242	56.0	159.9	218.6
243	20.0	20.5	21.3
244	39.0	35.3	44.3
245	57.0	56.9	65.6
246	182.0	230.2	308.6
247	159.0	335.4	254.0
248	148.0	393.6	598.3
249	117.0	332.1	250.5
250	50.0	125.8	205.4
251	65.0	134.0	191.1
252	164.0	244.2	257.7
253	71.0	195.0	253.7
254	38.0	16.5	16.5
255	38.0	35.7	38.4
256			
257	36.0	33.5	34.7
258	72.0	74.8	54.0
259			
261			
262	310.0	348.3	685.4
263	246.0	272.6	459.5
264			
265	195.0	132.9	130.9
266	245.0	180.0	188.3
267	227.0	253.6	212.8
268	86.0	117.0	157.1
269	47.0	244.3	413.5
270	58.0	126.6	156.9
271	84.0	58.0	69.1
272	99.0	147.5	261.5
273	239.0	364.4	861.5
274	22.0	304.3	255.5
275	60.0	145.0	142.6
276	77.0	502.6	993.5
278			
285	54.0	66.8	89.5
289	111.0	221.8	253.7
290	128.0	170.8	147.7
291	86.0	171.2	359.7
292	58.0	52.9	43.6
293	13.0	16.1	16.4
294	11.0	58.9	49.2
295	19.0	160.7	207.6
296	29.0	172.2	229.6
297	28.0	244.6	481.9
298	146.0	53.1	36.5
299	64.0	33.6	47.6
300	46.0	52.8	63.3
301	19.0	20.6	20.9
302			
303			
304	22.0	29.5	31.9
305	18.0	86.9	56.2
306	9.0	101.9	82.8
307	5.0	229.7	169.1
308	8.0	8.6	15.8
309	5.0	4.0	4.0
310	18.0	238.0	244.6
311	20.0	182.8	238.8
312	19.0	69.9	118.0
314	20.0	39.9	62.9
315	20.0	44.3	66.5
316	20.0	164.9	343.2
317	37.0	109.9	130.1
322	31.0	268.2	236.7
323	54.0	188.7	366.6
324	39.0	120.3	99.3
325	21.0	35.1	38.9
326	32.0	137.2	153.2
327	29.0	54.9	45.7
328			
329	18.0	41.5	53.7
330	25.0	217.2	234.0
331			
332			
333	18.0	17.9	17.8
334	27.0	31.6	30.7
335	21.0	71.7	75.3
336	197.0	35.2	63.0
337	139.0	75.3	140.9
338	103.0	237.3	468.1
339	45.0	86.6	112.3
340	34.0	163.3	337.4
341	31.0	113.7	146.8
342	26.0	102.8	178.4
343	55.0	189.3	332.1
344	49.0	282.5	483.0
345	29.0	159.4	296.7
346	16.0	111.0	239.8

Table 3-9. Model Results Comparison for PM-10 at Site 4

Julian Day No.	Measured Concen. (ug/m3)	FDM Predicted Concen. (ug/m3)	ISCST Predicted Concen. (ug/m3)	Julian Day No.	Measured Concen. (ug/m3)	FDM Predicted Concen. (ug/m3)	ISCST Predicted Concen. (ug/m3)
215	36.0	40.7	36.7	274	23.0	109.0	157.7
216				275	26.0	120.0	205.7
217	36.0	40.2	43.2	276	50.0	96.7	151.3
218				278			
219	35.0	53.0	192.8	285	43.0	48.2	48.9
220				289	89.0	135.4	138.0
221	71.0	108.9	278.9	290	38.0	80.1	146.0
222				291	56.0	90.0	81.4
223	47.0	89.2	180.0	292	55.0	141.6	108.6
224				293	16.0	15.8	17.7
225	103.0	99.0	206.2	294	11.0	58.3	97.5
226	87.0	100.5	163.8	295	16.0	94.3	197.5
227				296	17.0	31.2	48.0
228	27.0	137.4	777.0	297	18.0	21.2	16.0
229				298	59.0	135.7	145.5
230	26.0	74.6	110.7	299	20.0	18.3	17.3
231	76.0	448.8	691.2	300	113.0	76.9	51.7
232	49.0	192.4	152.7	301	22.0	171.4	281.7
233	48.0	83.0	123.8	302	31.0	155.3	254.1
234	89.0	146.1	130.5	303	17.0	206.8	243.1
235	60.0	84.0	85.6	304	24.0	60.8	78.0
236	41.0	35.4	35.3	305			
237	20.0	22.2	20.0	306	7.0	6.4	6.2
238	47.0	65.8	34.8	307	4.0	4.2	4.8
239	99.0	341.0	909.7	308	12.0	65.1	94.4
240	250.0	316.4	801.6	309	9.0	154.2	219.9
241	119.0	194.5	195.4	310	14.0	14.6	15.3
242	84.0	120.4	131.3	311	16.0	13.1	13.2
243	18.0	75.1	48.7	312	17.0	22.5	13.0
244	52.0	29.6	23.8	314	19.0	45.6	23.1
245	72.0	76.6	53.8	315	13.0	78.4	45.9
246	170.0	74.2	73.5	316	21.0	28.6	22.6
247	181.0	98.7	82.8	317	23.0	40.9	22.0
248	225.0	51.9	48.7	322	23.0	21.3	22.7
249	97.0	70.9	51.3	323	29.0	29.6	28.4
250	57.0	56.3	25.0	324	62.0	24.6	24.4
251	59.0	74.7	46.0	325	24.0	45.6	61.0
252	163.0	108.5	76.7	326	35.0	39.3	52.2
253	165.0	125.0	252.1	327	27.0	78.4	62.6
254	42.0	216.6	361.2	328	31.0	38.0	35.1
255	49.0	187.7	296.3	329	19.0	30.9	38.9
256	42.0	49.5	106.4	330	26.0	64.9	48.9
257	26.0	37.6	37.6	331	12.0	30.8	40.5
258	43.0	60.6	91.5	332	9.0	6.7	6.8
259	99.0	96.4	157.1	333	16.0	17.1	18.5
261	152.0	112.1	94.8	334	28.0	41.9	36.9
262	180.0	79.4	86.9	335	10.0	14.4	14.3
263	232.0	131.7	144.3	336	41.0	53.5	23.7
264	124.0	130.4	121.9	337	26.0	122.6	53.1
265	93.0	73.9	76.8	338	28.0	30.4	38.0
266	143.0	62.8	58.6	339	24.0	43.6	26.6
267	29.0	54.8	61.1	340	50.0	244.9	209.7
268	37.0	110.5	223.2	341	32.0	74.2	35.2
269	36.0	178.8	203.3	342	28.0	32.8	26.0
270	29.0	124.1	153.0	343			
271	52.0	175.0	181.1	344	38.0	47.2	46.0
272	40.0	63.4	51.2	345	25.0	32.6	21.1
273	63.0	77.5	65.7	346	32.0	323.5	255.6

Table 3-10. Model Results Comparison for PM-10 at Site 5

Julian Day No.	Measured Concen. (ug/m3)	FDM Predicted Concen. (ug/m3)	ISCST Predicted Concen. (ug/m3)	Julian Day No.	Measured Concen. (ug/m3)	FDM Predicted Concen. (ug/m3)	ISCST Predicted Concen. (ug/m3)
215				274	11.0	24.1	25.7
216	25.0	25.0	25.0	275	24.0	39.0	63.2
217				276	30.0	48.8	70.4
218	34.0	34.0	34.0	278	14.0	14.0	14.0
219				285	79.0	39.7	40.3
220	29.0	29.7	29.7	289	31.0	40.4	46.7
221				290	21.0	28.0	37.3
222	56.0	56.4	56.7	291	42.0	41.0	41.0
223				292	24.0	24.0	24.0
224	33.0	41.1	48.2	293	17.0	14.2	14.4
225				294	11.0	25.1	41.0
226	60.0	65.4	71.2	295	17.0	34.7	62.4
227	37.0	37.0	37.0	296	13.0	19.1	25.9
228	19.0	32.2	49.9	297	16.0	16.0	16.0
229	31.0	31.9	33.0	298	20.0	35.4	49.2
230	21.0	23.5	24.7	299	19.0	15.1	15.2
231	29.0	39.9	48.1	300			
232				301	18.0	29.2	38.5
233	33.0	45.0	57.2	302	31.0	42.9	57.5
234	34.0	57.8	90.2	303	17.0	29.2	44.7
235	51.0	55.9	66.8	304			
236	36.0	35.0	35.0	305	22.0	16.0	17.1
237				306	6.0	6.0	6.0
238	27.0	27.0	27.0	307	5.0	3.0	3.0
239	28.0	28.0	28.0	308	6.0	13.5	17.7
240	35.0	35.0	35.1	309	6.0	23.0	33.0
241	59.0	59.0	59.0	310	11.0	11.2	11.2
242	41.0	32.2	35.8	311	13.0	13.0	13.0
243	21.0	23.4	24.8	312	13.0	13.0	13.0
244	29.0	20.7	21.3	314	18.0	21.7	23.6
245	49.0	45.0	45.0	315	19.0	17.6	20.3
246	44.0	44.0	44.0	316	17.0	17.6	18.1
247	45.0	45.0	45.0	317	24.0	22.0	22.0
248	38.0	38.0	38.0	322	20.0	18.9	18.8
249	38.0	37.0	37.0	323	21.0	21.0	21.0
250	33.0	25.0	25.0	324	14.0	14.0	14.0
251	46.0	46.0	46.0	325	23.0	28.7	33.9
252	44.0	45.8	46.8	326	21.0	23.8	25.9
253	40.0	51.3	60.1	327	26.0	26.1	26.0
254	25.0	34.5	47.9	328	30.0	33.7	35.1
255	28.0	46.0	63.3	329	18.0	18.6	19.4
256	27.0	57.3	93.2	330	20.0	20.0	20.0
257	30.0	27.4	28.5	331	9.0	10.8	13.8
258	30.0	35.5	43.7	332	8.0	7.9	8.2
259	56.0	60.4	66.3	333	17.0	16.4	17.3
261	51.0	58.0	66.4	334	25.0	25.7	25.9
262	57.0	64.7	76.3	335	10.0	10.0	10.0
263	64.0	66.2	66.7	336	14.0	12.0	12.0
264	59.0	59.1	59.0	337	16.0	16.2	16.1
265	51.0	58.7	64.8	338	24.0	25.6	33.7
266	45.0	45.0	45.0	339	21.0	21.0	21.0
267	12.0	13.2	14.0	340	23.0	23.0	23.0
268	37.0	47.7	70.0	341	32.0	29.0	29.0
269	21.0	22.6	24.5	342	28.0	26.0	26.0
270	23.0	73.6	105.1	343	37.0	39.5	43.6
271	25.0	24.0	24.0	344	35.0	36.9	39.2
272	33.0	31.6	31.2	345	22.0	21.0	21.0
273	40.0	40.0	40.0	346	14.0	35.3	59.6

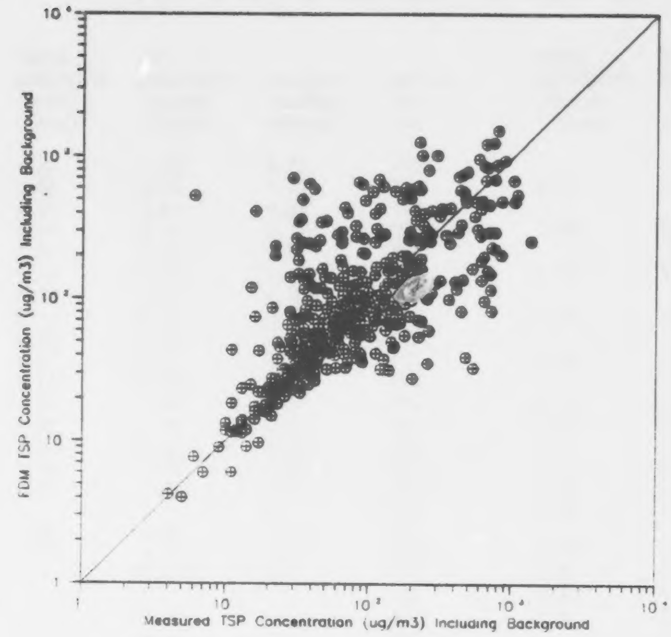

FIGURE 3-1 FDM EVALUATION FOR TSP

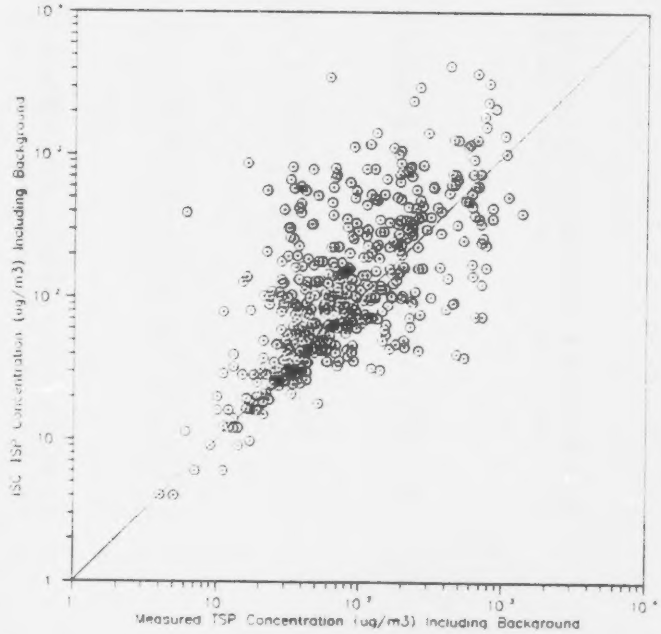

FIGURE 3-2 ISC EVALUATION FOR TSP

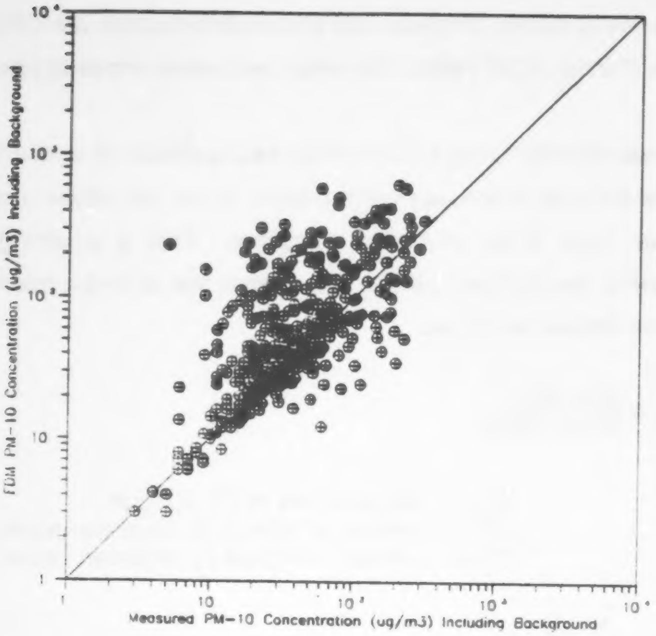

FIGURE 3-3 FDM EVALUATION FOR PM-10

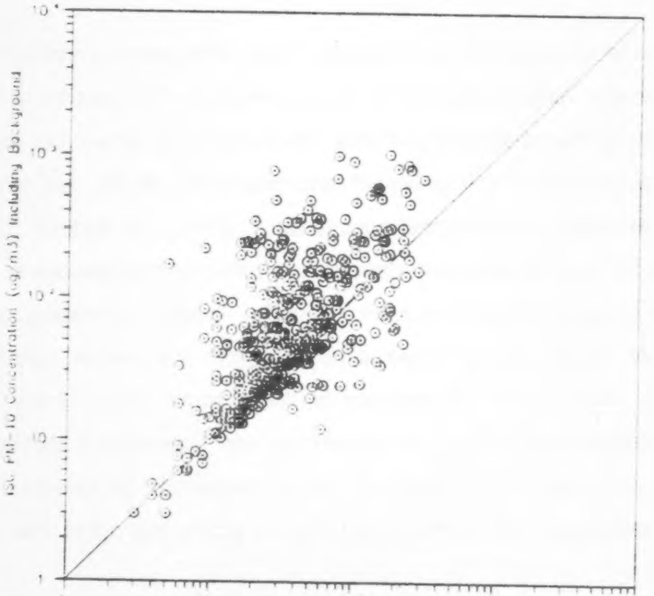

FIGURE 3-4 ISC EVALUATION FOR PM-10

two. For FDM, the TSP predicted results are within a factor of two of the measured results for 72 percent of the values. For the FDM PM-10 results, the measured and predicted values are within a factor of two for 73 percent of the values. For the ISCST results, the same comparison shows 63 percent for TSP and 65 percent for PM-10.

EPA has recently been recommending a new method for unpaired data comparisons (Cox et. al., 1988). It also centers on the concept of accuracy within a factor of two, but utilizes a more complicated comparison. There are two steps in the evaluation procedure. First, a screening computation is completed using two quantities, the fractional bias for the average values and a fractional bias for the standard deviation. They are defined as follows:

$$FB = \frac{OB - PR}{(OB + PR)/2}$$

where:
FB = fractional bias of the average
OB = average of highest 25 observed values
PR = average of highest 25 predicted values

$$FO = \frac{S_o - S_p}{(S_o + S_p)/2}$$

where:
FO = fractional bias of the standard deviation
S_o = standard deviation of the highest 25 observed values
S_p = standard deviation of the highest 25 predicted values

The screening evaluation is performed by computing both of the above parameters, and plotting on a special graph. The second level of analysis is more complex. The second level is called the statistical test and involves using the same fractional bias computation as above, but rather than using the average and standard deviations of the observed and predicted values, the technique uses a parameter called the robust estimate of the highest concentration (RHC). In addition, the computation of the fractional bias is done for several averaging periods and differing meteorological conditions and the results used to compute a composite performance measure. Finally, a statistical technique called "bootstrapping" is used where values are extracted at random from the overall data set to create a "sampled" data set, which is used in the computation of these same performance measures. By conducting this random sampling many times, the statistician can determine if differences in model performance are statistically significant. More details on the technique can be found in Cox's paper.

Using the screening technique, the results of the paired in space, but not in time, and the results

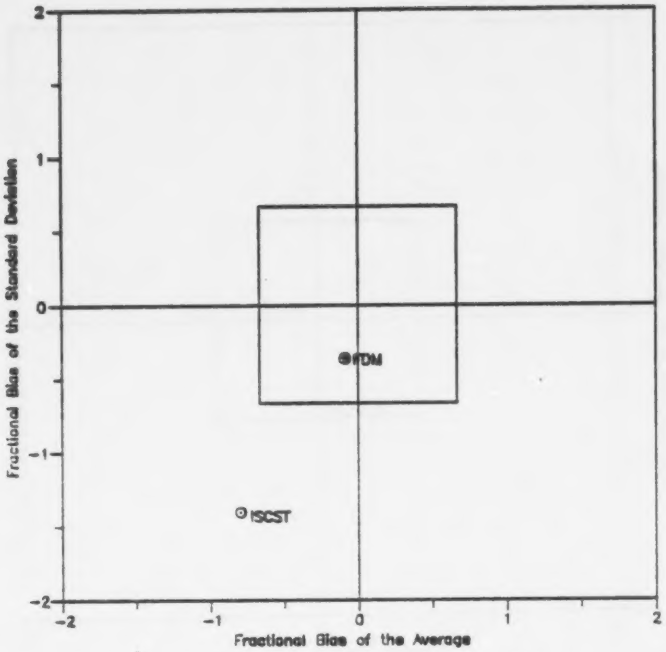

Figure 3–5. Screening Evaluation Results for TSP Unpaired in Time and Space

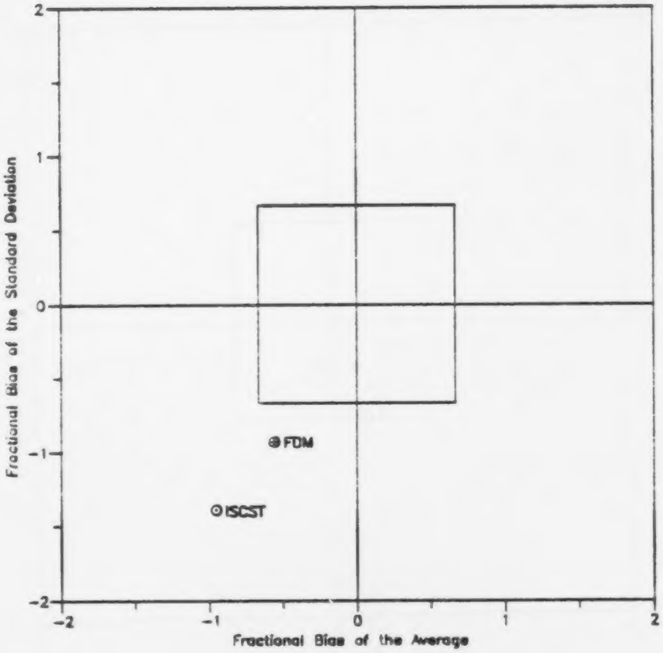

Figure 3–6. Screening Evaluation Results for PM–10 Unpaired in Time and Space

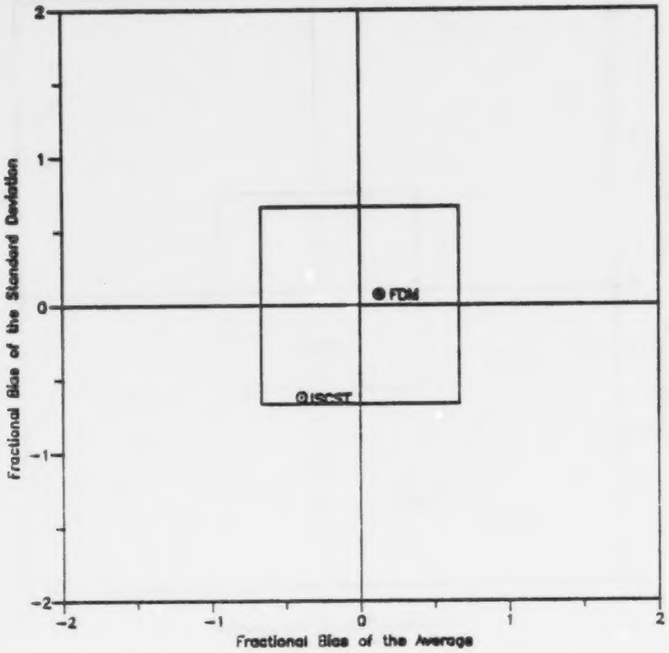

Figure 3-7. Screening Evaluation Results for TSP Unpaired in Time for Site 1

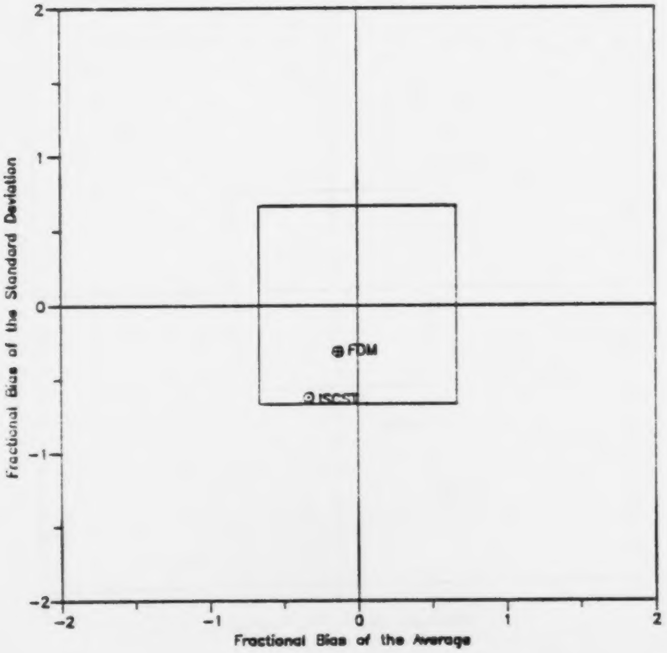

Figure 3-8. Screening Evaluation Results for PM-10 Unpaired in Time for Site 1

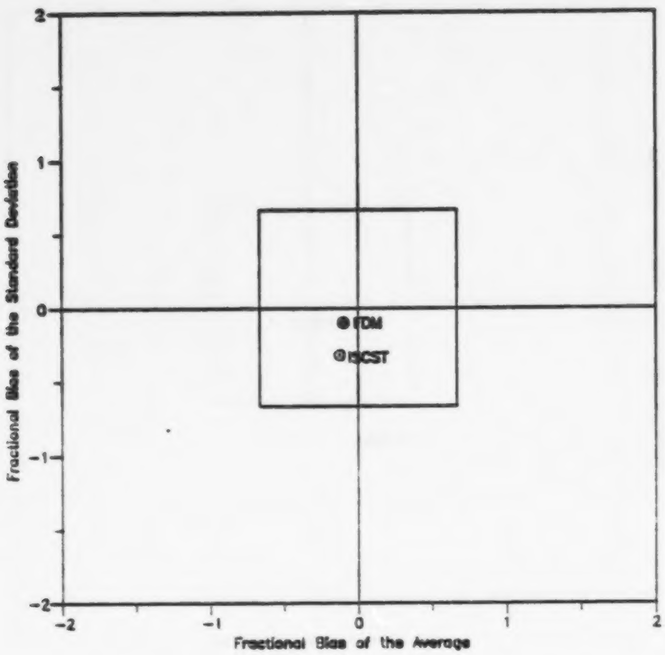

Figure 3-9. Screening Evaluation Results for TSP Unpaired in Time for Site 2

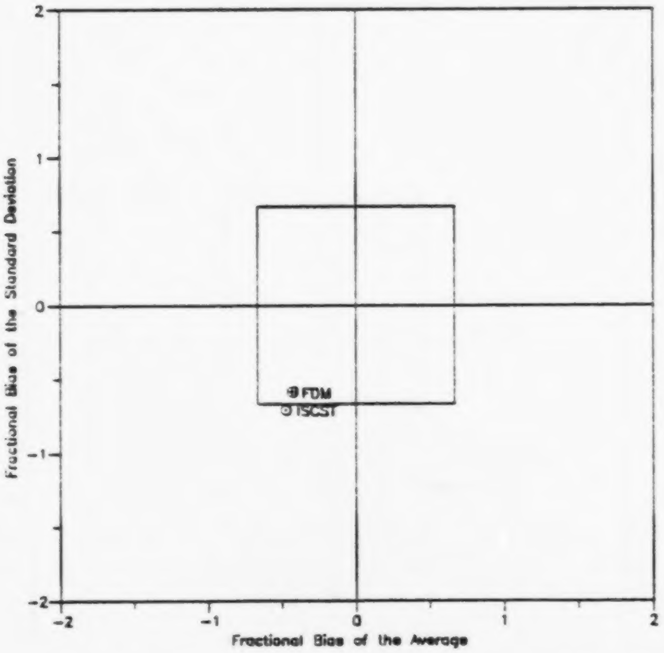

Figure 3-10. Screening Evaluation Results for PM-10 Unpaired in Time for Site 2

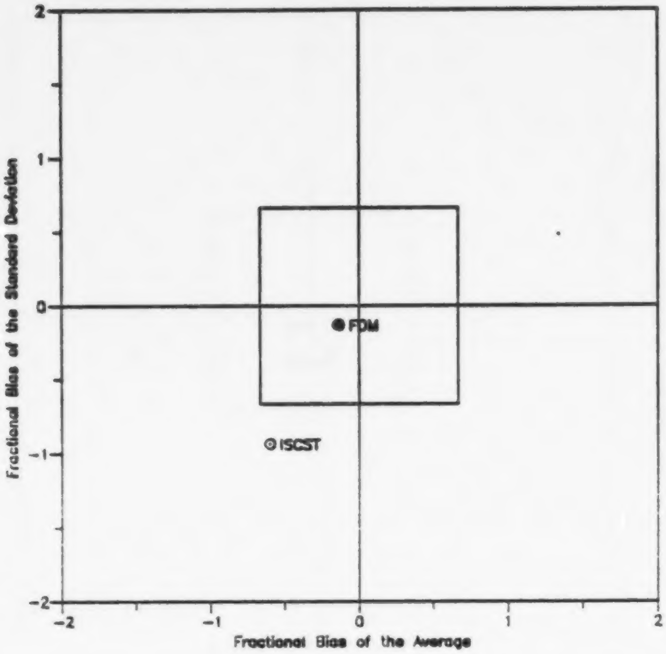

Figure 3-11. Screening Evaluation Results for TSP Unpaired in Time for Site 3

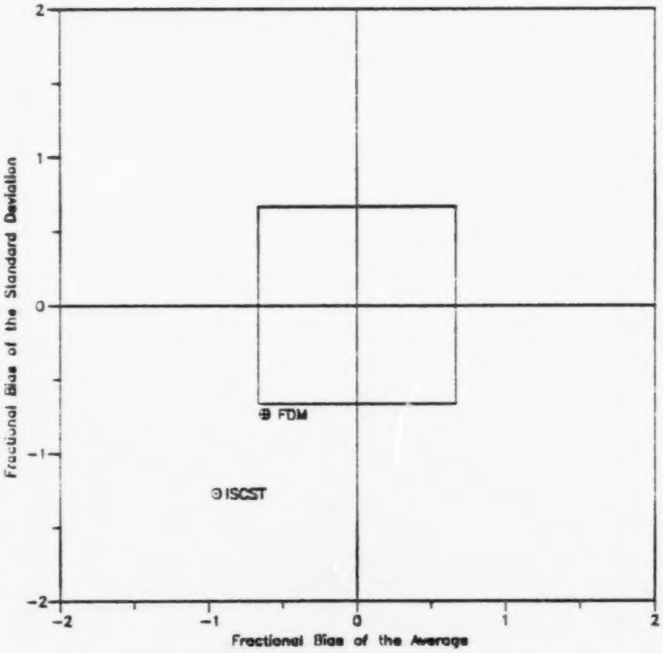

Figure 3-12. Screening Evaluation Results for PM-10 Unpaired in Time for Site 3

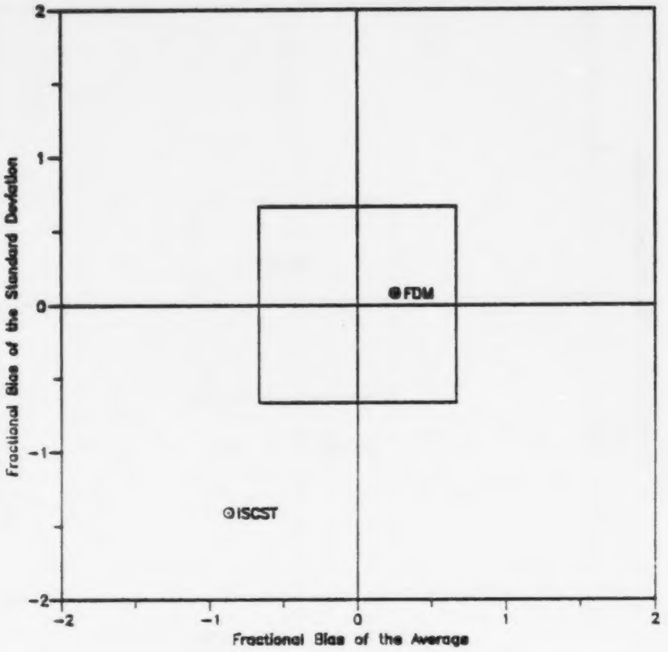

Figure 3–13. Screening Evaluation Results for TSP Unpaired in Time for Site 4

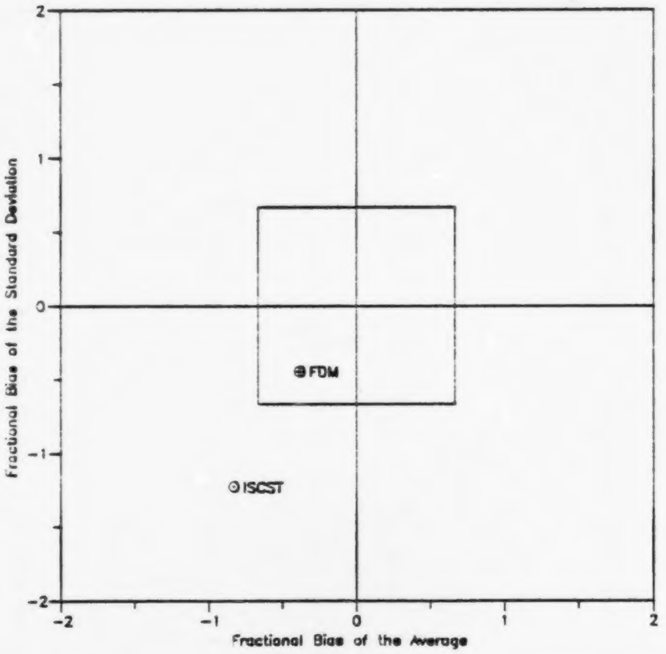

Figure 3–14. Screening Evaluation Results for PM–10 Unpaired in Time for Site 4

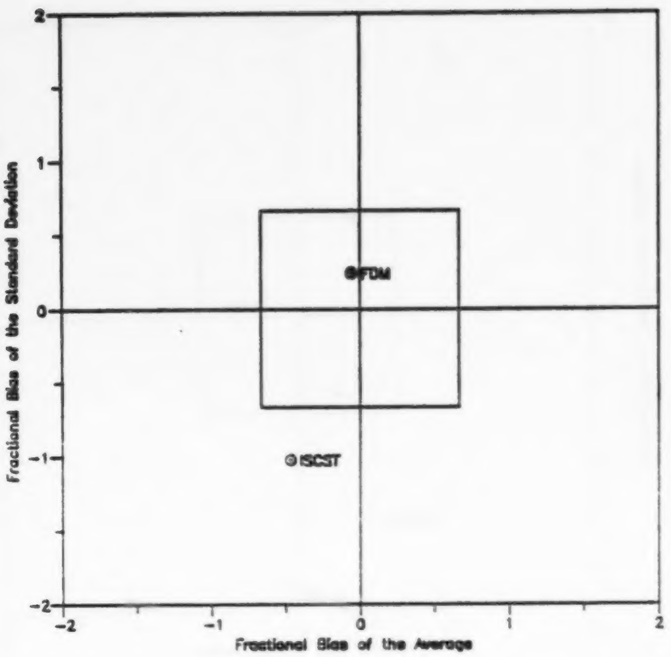

Figure 3-15. Screening Evaluation Results for TSP Unpaired in Time for Site 5

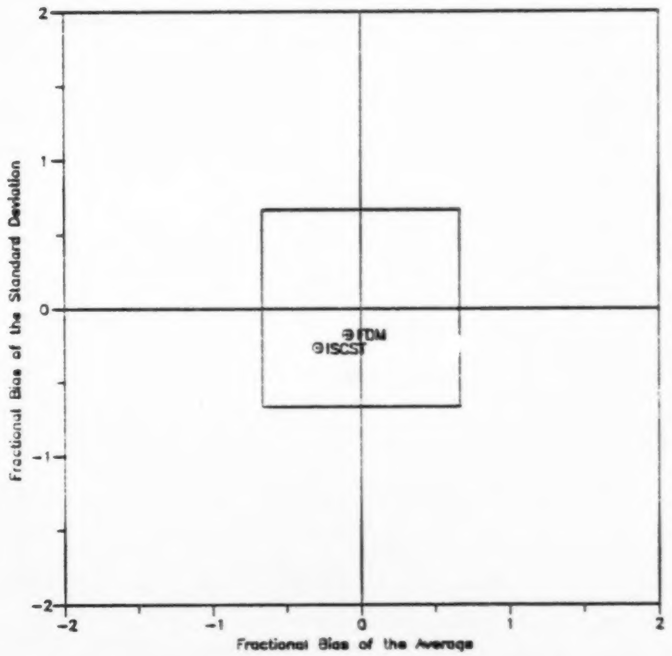

Figure 3-16. Screening Evaluation Results for PM-10 Unpaired in Time for Site 5

- The bootstrapping technique calls for the construction of a number of trial "years" by sampling the data set. Since sampling a four-month, semi-continuous data set to create a full year of data, would extend the data beyond its measurement bounds, the sampling was performed only to create a trial set equivalent in size to the original data set.

The bootstrapping analysis was completed for both TSP and PM-10 for both models and was performed for both the paired in space but not in time data sets as well as the completely unpaired data set. Although not customarily presented in this fashion, the frequency distribution of the Fraction Bias of the RHC's calculated in the bootstrapping analysis for TSP are shown in Figure 3-17 and 3-18 for TSP and PM-10 for the unpaired data comparisons. Similar figures for the individual sites in the paired in space but not in time comparisons are depicted in Figures 3-19 through 3-28. Note that the figure presents the fractional bias, not the absolute fractional bias. The figures show the same pattern as observed in the screening evaluation. For all cases, the FDM model predictions are closer to a fractional bias of zero than the ISCST model predictions. The PM-10 results for FDM show a greater tendency toward over-prediction than the TSP results, but in all cases the FDM predictions are still more accurate than the ISC prediction.

One important aspect of the model's performance is that the improvement in prediction of FDM not be simply an artifact of the particular cases examined, but truly representative of a statistical superiority. In the figures, this is illustrated by a clear separation in the statistical distributions of the bootstrapped model results. For most sites this separation is very evident in the figures. For example, in the totally unpaired data comparisons, the separation between the FDM distribution and the ISCST distribution is virtually complete (almost no overlap). For a few of the sites, the separation is not as clear. This is most evident at site 2, and somewhat evident in all of the PM-10 plots. Further examination of these results indicates that site 2 is unusual in that a major emitting source (the primary haul road of the mine) is extremely close to the receptor (within 100 meters). The major advantage to the FDM is the ability to more accurately represent deposition, but for this very close receptor, little deposition has occurred, and the improvement to be offered by FDM is not available. The same general conclusion applies to all the PM-10 results. Although PM-10 will still undergo deposition at a mining operation due to turbulent processes, the deposition rate is much less than for larger particles. As a result, the FDM predictions will be closer to the ISC predictions for PM-10 than for TSP.

The previous discussion would lead to the conclusion that generally, the FDM model performs acceptably with the data, while the ISCST model does not. In actuality, as earlier figures show, both models can perform reasonably well for the some of the data points. However, ISCST has the tendency for large over-prediction on few days. Unfortunately, it is these days which are the focus of the permitting regulations. Most regulations concern the maximum or second highest concentration, so the ISCST over-

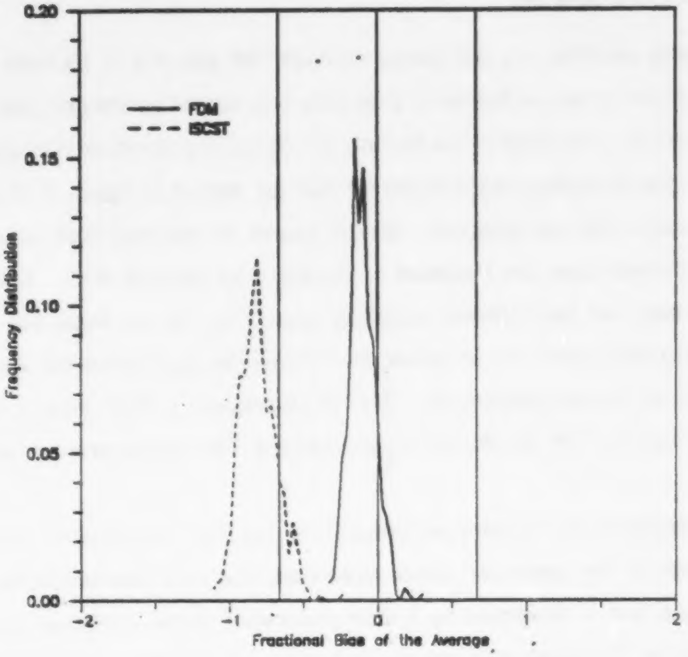

Figure 3–17. Fractional Bias Distributions for TSP Unpaired in Time and Space

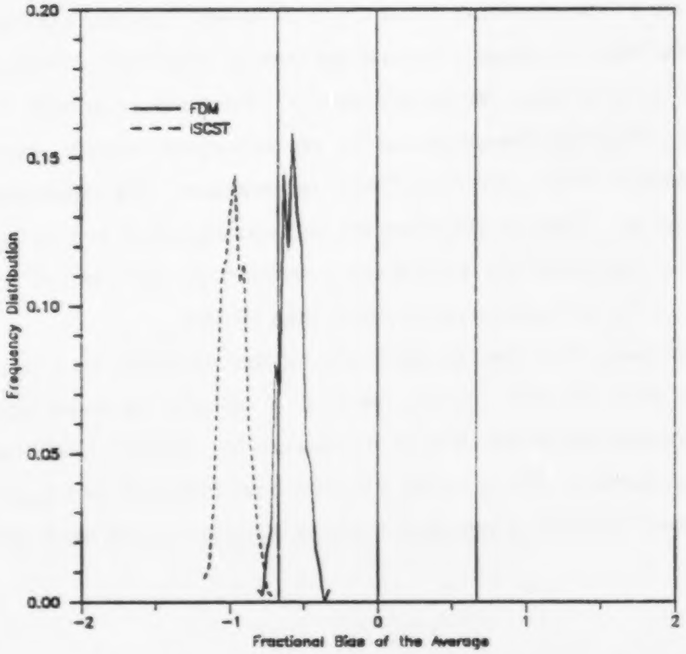

Figure 3–18. Fractional Bias Distributions for PM-10 Unpaired in Time and Space

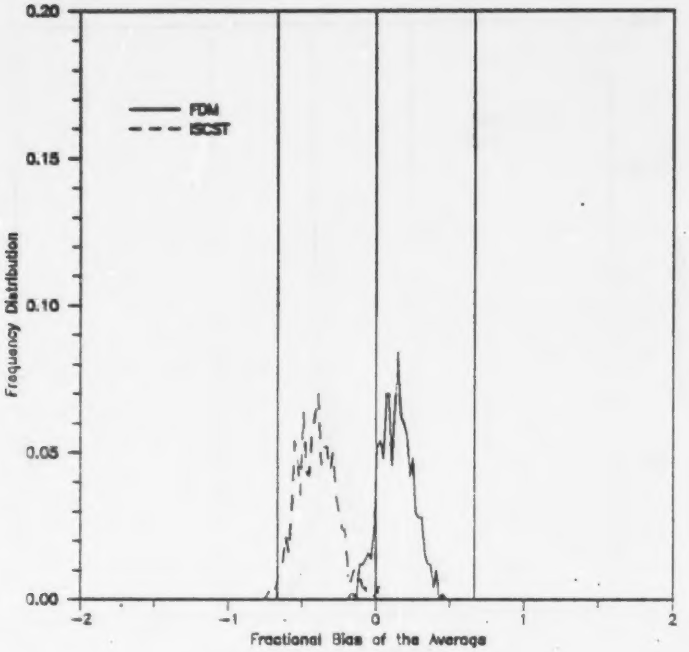

Figure 3-19. Fractional Bias Distributions for TSP Unpaired in Time for Site 1

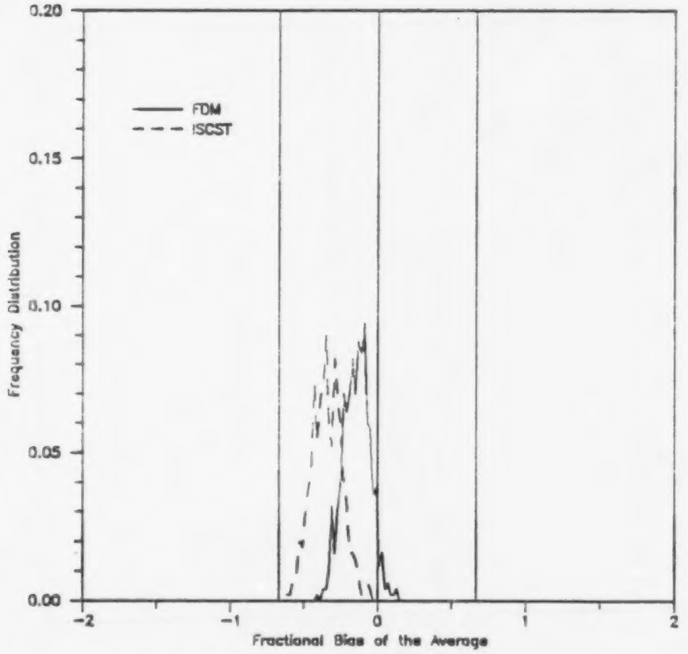

Figure 3-20. Fractional Bias Distributions for PM-10 Unpaired in Time for Site 1

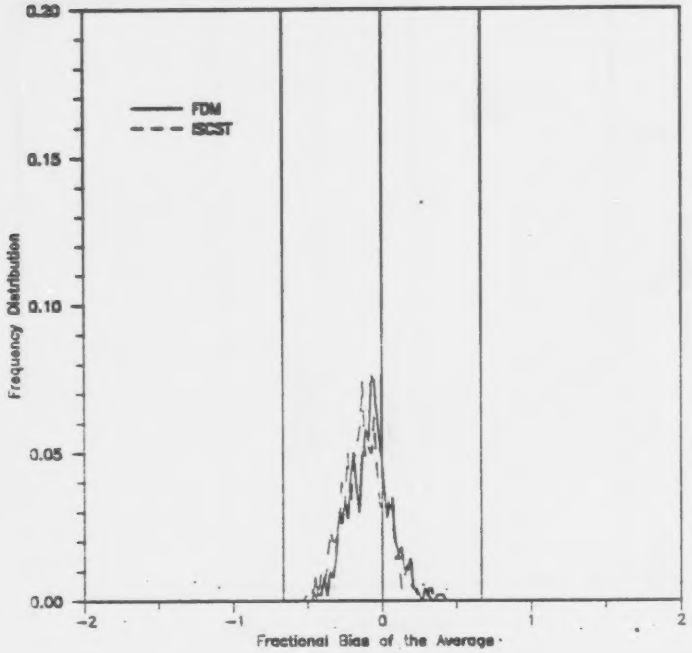

Figure 3-21. Fractional Bias Distributions for TSP Unpaired in Time for Site 2

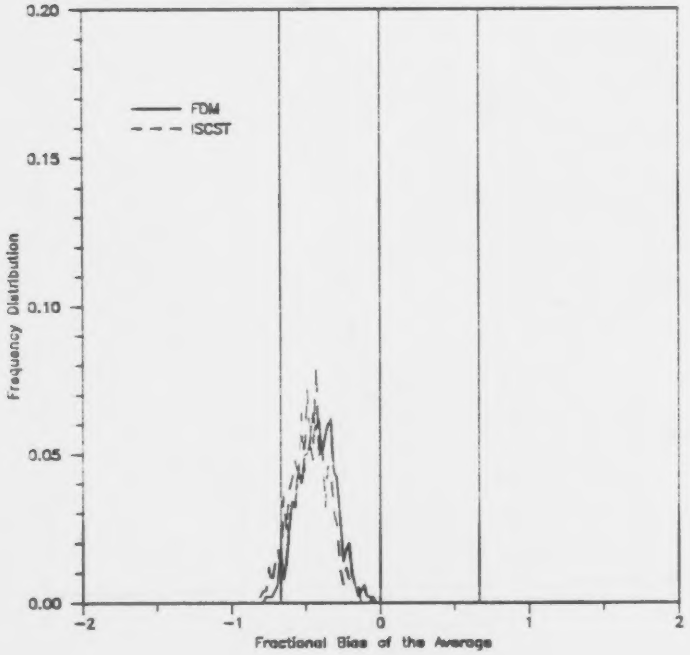

Figure 3-22. Fractional Bias Distributions for PM-10 Unpaired in Time for Site 2

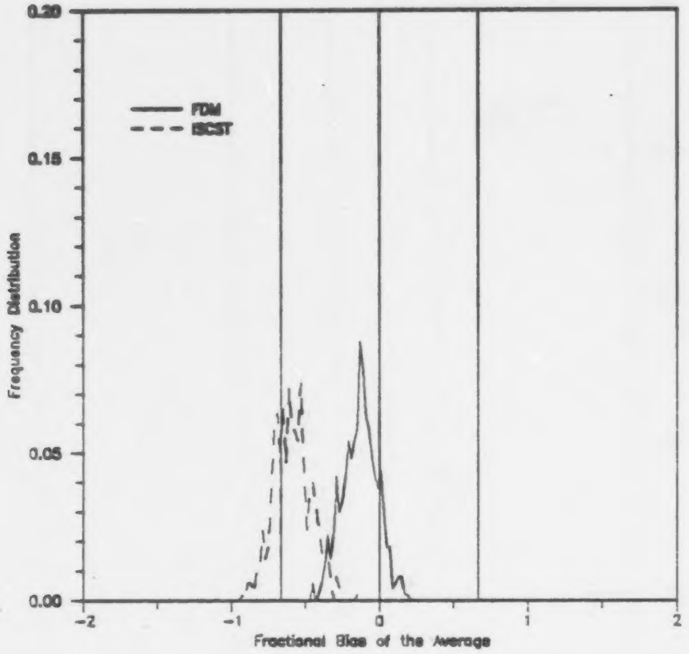

Figure 3-23. Fractional Bias Distributions for TSP Unpaired in Time for Site 3

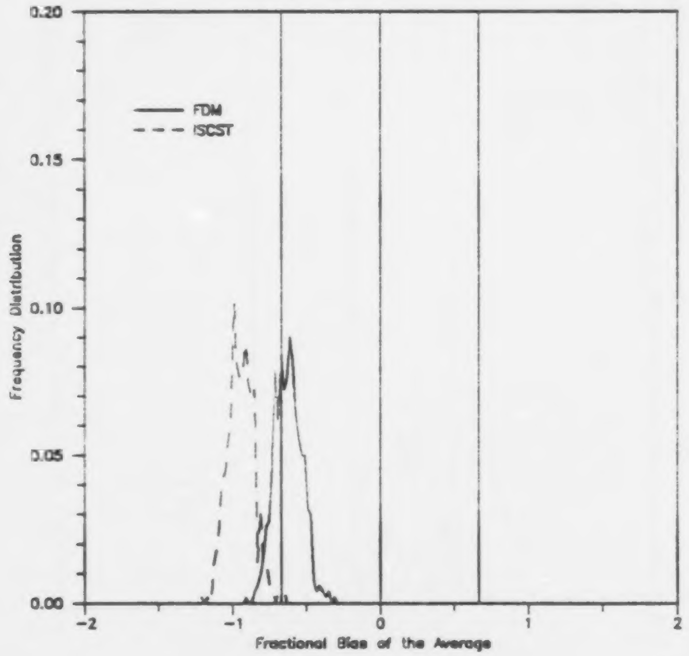

Figure 3-24. Fractional Bias Distributions for PM-10 Unpaired in Time for Site 3

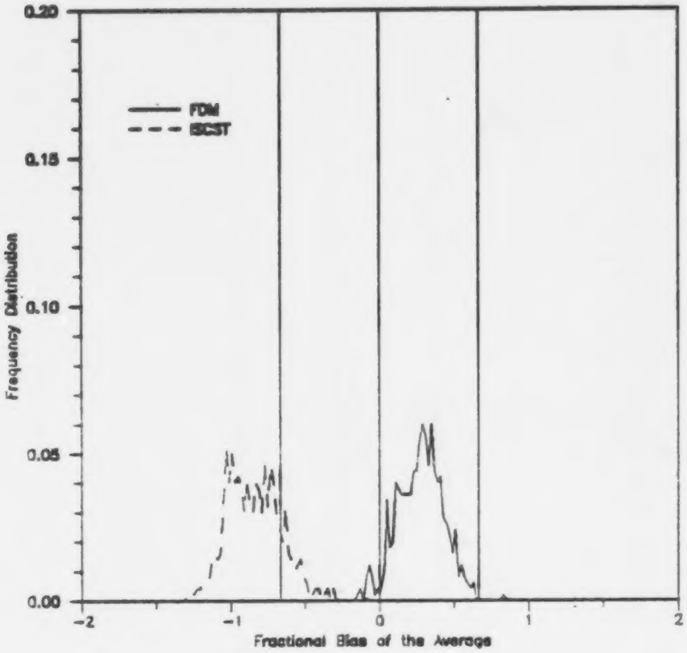

Figure 3-25. Fractional Bias Distributions for TSP Unpaired in Time for Site 4

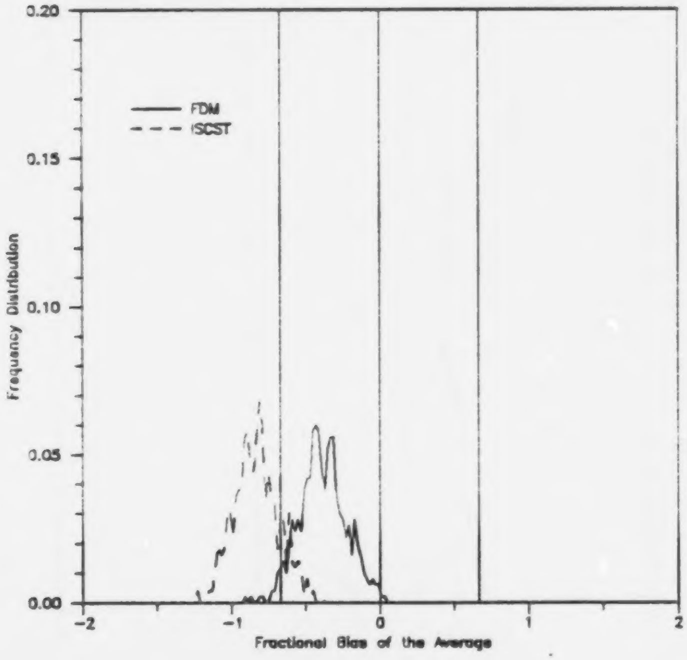

Figure 3-26. Fractional Bias Distributions for PM-10 Unpaired in Time for Site 4

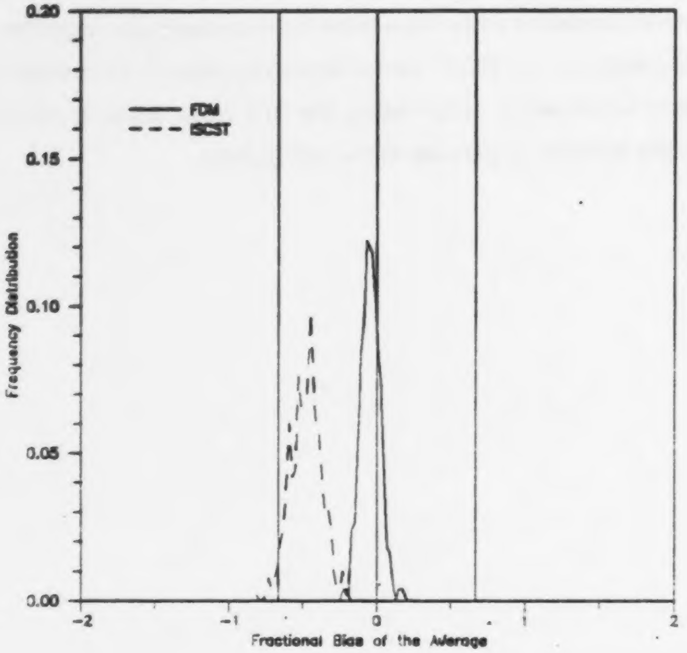

Figure 3-27. Fractional Bias Distributions for TSP Unpaired in Time for Site 5

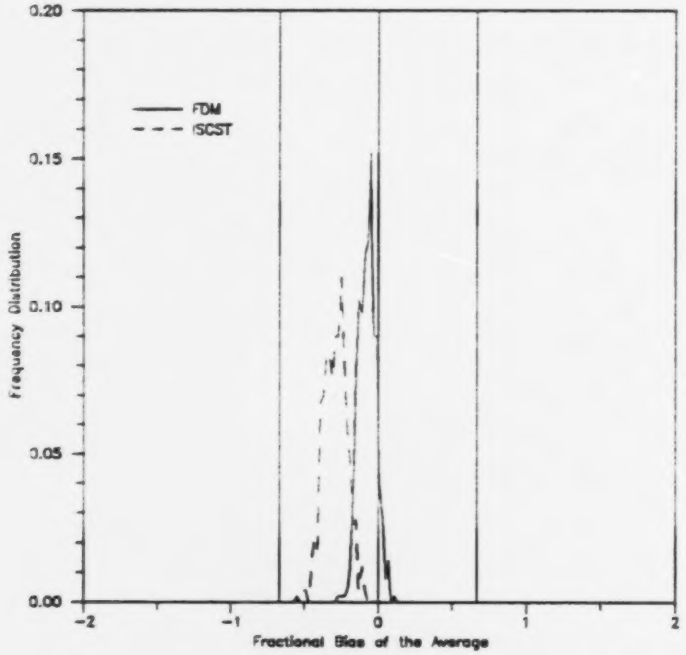

Figure 3-28. Fractional Bias Distributions for PM-10 Unpaired in Time for Site 5

prediction on these days causes very misleading results in air quality permitting studies. It tends to occur under stable, low wind speed conditions.

One of the major advantages of the FDM approach is the avoidance of these large over-predictions. The improved prediction occurs due to the superior deposition algorithm in the FDM. During low wind speed stable conditions, the ISCST model allows very high concentrations to be predicted, not reflecting the deposition which would occur during the long travel times to the receptor. FDM more accurately represents the behavior of particles in the atmosphere.

4.0 CONCLUSIONS

The previous analysis has determined that the FDM Model performs generally well in characterizing particulate concentrations in the vicinity of the fugitive dust source. The ISCST model also performed well for the bulk of the samples analyzed, but failed poorly on the high end of the statistical distribution, leading to large over-predictions of the highest and second highest concentrations, which are the focus of many air quality regulations for short-term particulate concentrations. The FDM Model is judged to be superior in predicting the impacts from fugitive dust sources for the data evaluated in this study.

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2. Cox, W. M. "Protocol for Determining the Best Performing Model", U.S.EPA. August 1988.

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Fugitive Dust Model (FDM)
Third Validation Study

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Table of Contents

1.0 Introduction... A(3)-1

2.0 Methodology and Model Inputs.. A(3)-4

3.0 Air Quality Modeling Results.. A(3)-5

4.0 Conclusions... A(3)-13

References... A(3)-15

1.0 Introduction

The Fugitive Dust Model (FDM) was developed as an alternative to the previously recommended Industrial Source Complex Model (ISC) for the purposes of computing fugitive dust impacts. Two previous validation studies were performed using measured air quality and meteorological data from surface mining operation. The results of the both validation studies were very encouraging. One major uncertainty in any air quality investigation centering on fugitive dust is the emission rate. Unlike a stack source, emissions of fugitive dust cannot be contained and measured. Therefore, the previous two validation studies relied on published emission factors and mine activity data to estimate emissions. While such applications represent the real applications of such models and are very relevant in the current regulatory setting, uncertainty is invariably introduced with the emission factor method of emission information. As an additional validation effort for FDM, a third validation study was performed using data collected over a number of years at the Hanford federal reservation in eastern Washington. The Hanford data may well represent the most comprehensive study of particulate behavior in the atmosphere in existence.

The purpose of the Hanford experiments was to quantify the dispersion and in particular the deposition, of emitted particulate matter. Although applicable to fugitive dust, the Hanford experiments were not aimed at fugitive dust. A series of experiments were performed over many years where known release rates of particulate tracers were emitted from a point source, and concentrations measured at an extensive array of sampling locations. The particulate data base has been termed the "Hanford 67" data base because experiments began at the site in 1967.

TRC has previously conducted a detailed investigation of the Industrial Source Complex (ISC) Model using the Hanford data base, and the results of that investigation are reported in Cole (1988). We have not attempted to detail the conduct of that investigation in the current document. Rather, the interested reader is referred to the Cole document for more details on the adaptation of the Hanford data base to the ISC model. In the current investigation, the input streams from the Cole runs of ISC were adapted to make input streams for the FDM model.

Briefly, the Hanford data base consists of two general types of experimental results: single tracer experiments and dual tracer experiments. Both were examined here, but the dual tracer experiments are of the greatest interest in the current investigation. In the experiments, release rates of zinc-sulfide or fluorescein, two particulate tracers, were fixed and measured. Concentrations of these pollutants were measured in an array of samplers arranged on arcs centered at the release point. Cross-wind integrated concentrations formed the primary measured data used in the experiments.

In the single tracer experiments, a single particulate tracer was released and concentrations measured and integrated. The two models were used to compute cross wind integrated concentrations for comparisons with the measured data. Concurrent meteorological data were available for all experiments. In the dual tracer experiments, zinc sulfide was released along with a known release rate of a tracer gas, sulfur-hexafluoride. The ratio of the particulate concentration to the gaseous concentration (normalized by the respective emission rates), called the concentration ratio, is a direct measure of the deposition rate. The ratio may be thought of as an indication of the fraction of the emitted particulate which is still suspended at the measurement distance.

The data from total of 45 separate single tracer experiments were available, while only 6 dual tracer experiments were available for analysis. In each experiment, concentrations were measured at from 3 to 7 downwind distances. For the purposes here, TRC examined all the data from four standard downwind distances: 200 meters, 800 meters, 1600 meters and 3200 meters.

2.0 Methodology and Model Inputs

The emissions source for purposes of the FDM model runs was assumed to be a point source at the specified release height which was generally 1 or 2 meters above the ground. The model was modified for the Hanford analysis to compute cross-wind integrated concentrations, rather than the external method used by Cole to develop cross-wind integrated concentrations for ISC.

Meteorological data were available for the Hanford site. Generally, a very high quality meteorological data set was available for the Hanford site, including the measurement of roughness height. Details of the Hanford meteorological and other site data are described in Cole report. For the dual tracer experiments, deposition velocity and gravitational settling velocity had actually been measured and reported by the Hanford project team. For these experiments only, the actual measured deposition velocities were entered to the model, rather than allow the model to compute these values using the CARB methodology.

3.0 AIR QUALITY MODELING RESULTS

The FDM and ISCST models were run for the 45 single tracer experiments and the 6 dual tracer experiments. Since tracer particles were used, it was not necessary to estimate background concentrations. There are a number of ways of comparing the model predictions with the measured data. The methods can generally be separated into two distinct classes of comparison: paired and unpaired comparisons. In paired data comparisons, a model's prediction at a particular receptor, for a particular period of time is compared to the measured values at that same location and time. In unpaired comparisons, a group of model predictions are analyzed to determine their own statistical properties. The measured data are similarly analyzed, and the results of the statistical evaluations are compared.

In one sense, the model's true evaluation is based on its ability to predict actual measured concentrations, and only paired data comparisons are indicative of this ability. However, consideration must be given to how the model is used in a regulatory setting. The models are used to predict compliance or non-compliance with regulatory criteria. It is not always relevant that they predict the location or time period of a particular concentration, but rather that they generally be reliable at predicting the levels at which a project is regulated (e.g. a maximum 24-hour particulate concentration at any property boundary location).

For the single tracer experiments, both paired and unpaired data comparisons have been conducted and will be presented. For the dual tracer experiments, insufficient data are available to compute the statistical parameters needed for unpaired data comparisons, thus only paired data comparisons are made here.

Single Tracer Experiments

For the paired data comparisons of the single tracer experiments, the comparison is presented in two formats. First, the measured versus predicted values are shown in Figures 3-1 and 3-2 for the FDM and ISC models respectively. These plots are in the form of "scatter plots" of the measured and predicted concentrations.

The figures do not show the dramatic illustration of the over-prediction tendency of ISC as compared with FDM that the first and, to a lesser degree, the second validation studies had indicated. Without the conduct of additional statistical analysis, the two figures appear very similar.

Air quality models are frequently quoted to predict within a factor of two, thus one means of comparison is to determine what number of the data points are within a factor of two. For FDM, the predicted results are within a factor of two of the measured results for 51 percent of the values. For the For the ISCST results, the same comparison shows only 45 percent. Thus although the figures appear

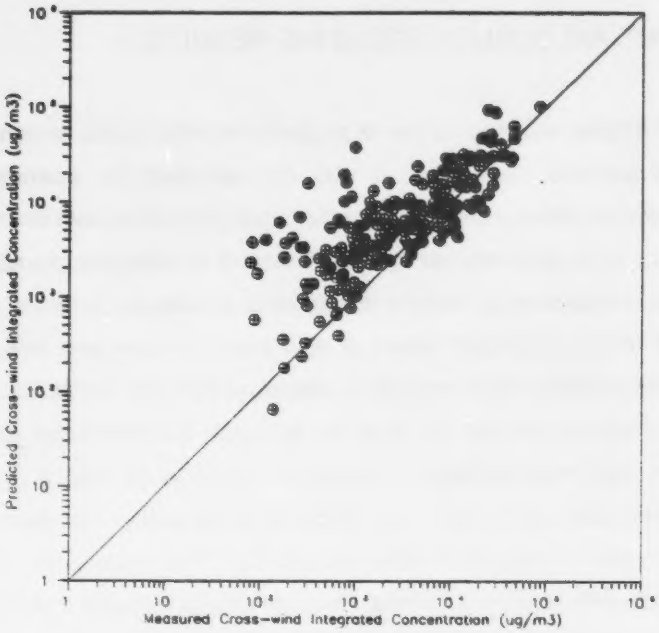


FIGURE 3-1 FDM EVALUATION FOR SINGLE TRACER

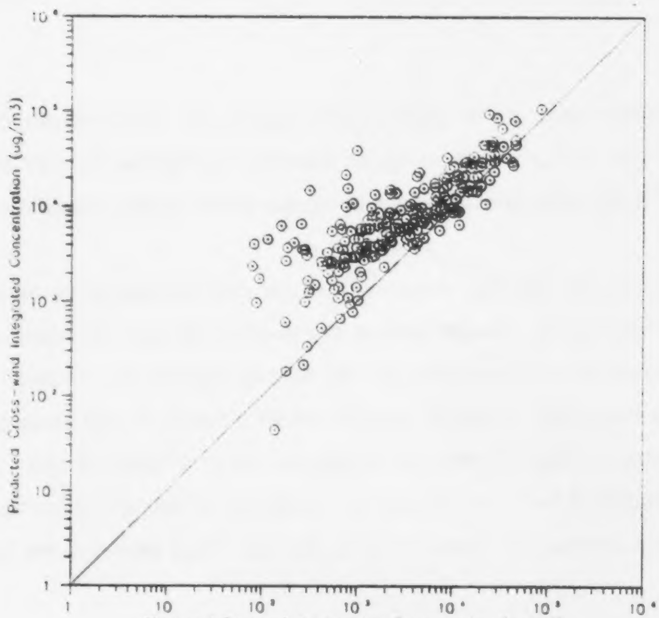


FIGURE 3-2 ISC EVALUATION FOR SINGLE TRACER

the same, the paired data comparison actually shows better performance for FDM than ISC.

EPA has recently been recommending a new method for unpaired data comparisons (Cox et. al., 1988). It also centers on the concept of accuracy within a factor of two, but utilizes a more complicated comparison. There are two steps in the evaluation procedure. First, a screening computation is completed using two quantities, the fractional bias for the average values and a fractional bias for the standard deviation. They are defined as follows:

$$FB = \frac{OB - PR}{(OB + PR)/2}$$

where:
FB = fractional bias of the average
OB = average of highest 25 observed values
PR = average of highest 25 predicted values

$$FO = \frac{S_o - S_p}{(S_o + S_p)/2}$$

where:
FO = fractional bias of the standard deviation
S_o = standard deviation of the highest 25 observed values
S_p = standard deviation of the highest 25 predicted values

The screening evaluation is performed by computing both of the above parameters, and plotting on a special graph. The second level of analysis is more complex. The second level is called the statistical test and involves using the same fractional bias computation as above, but rather than using the average and standard deviations of the observed and predicted values, the technique uses a parameter called the robust estimate of the highest concentration (RHC). In addition, the computation of the fractional bias is done for several averaging periods and differing meteorological conditions and the results used to compute a composite performance measure. Finally, a statistical technique called "bootstrapping" is used where values are extracted at random from the overall data set to create a "sampled" data set, which is used in the computation of these same performance measures. By conducting this random sampling many times, the statistician can determine if differences in model performance are statistically significant. More details on the technique can be found in Cox's paper.

Using the screening technique, the results of the Hanford single tracer experiments are depicted in Figure 3-3. The box at the center of the figure is an indication of the "factor of two" performance of the model. If the data plot within the box, then the model is said to have performed within a factor of two.

The results are consistent with the scatter plot findings, that FDM and ISC are very similar in performance with this data set. Both models exhibit a bias toward over-prediction with the single tracer experiments. The FDM performed slightly better than ISCST.

The second level of screening was a more complex undertaking. The technique has been developed primarily for predicting concentrations of sulfur dioxide or other gaseous compounds for which the data available generally include hourly observations of SO_2 concentration and meteorology on a continuous basis for a year or more. The measurement of particulate usually is done in 24-hour samples which are not continuous. For the current project, the samples were not done on a daily basis, thus modifications had to be made to the statistical evaluation methods to apply them to the current application. The modifications to the technique of Cox are summarized as follows:

- The samples varied in analysis time. Cox refers to a calculation of a "scientific" evaluation which uses 1-hour average concentrations. This computation was dispensed with. Given the single averaging time used here. the composite performance measure used here was equal to the Absolute Fractional Bias of the RHC values for each sample, regardless of sampling time.

- The bootstrapping technique calls for the construction of a number of trial "years" by sampling the data set. Since sampling a limited, non-continuous data set to create a full year of data, would extend the data beyond its measurement bounds, the sampling was performed only to create a trial set equivalent in size to the original data set.

The bootstrapping analysis was completed for both FDM and ISCST. Although not customarily presented in this fashion, the frequency distribution of the Fractional Bias of the RHC's calculated in the bootstrapping analysis for the single tracer experiments are shown in Figure 3-4. Note that the figure presents the fractional bias, not the absolute fractional bias. The figures show the same pattern as observed in the screening evaluation. The FDM model predictions are closer to a fractional bias of zero than the ISCST model predictions.

One important aspect of the model's performance is that the improvement in prediction of FDM not be simply an artifact of the particular cases examined, but truly representative of a statistical superiority. In the figures, this would be illustrated by a clear separation in the statistical distributions of the bootstrapped model results. It is clear that there is a small separation between the statistical distributions, but considerable overlap exists. The implication is that although the FDM performed better in the current analysis than the ISCST Model, the difference may not be statistically significant.

Dual Tracer Experiments

The dual tracer experiments differed from the single tracer experiments in that an actual measure of the deposition function in the model is made. The prediction of gaseous and particulate concentrations made by the model (normalized by the emission rate) are ratioed and the compared to similar ratios for the measured data. Paired data comparisons are shown for both models in Figure 3-5. It is clear from

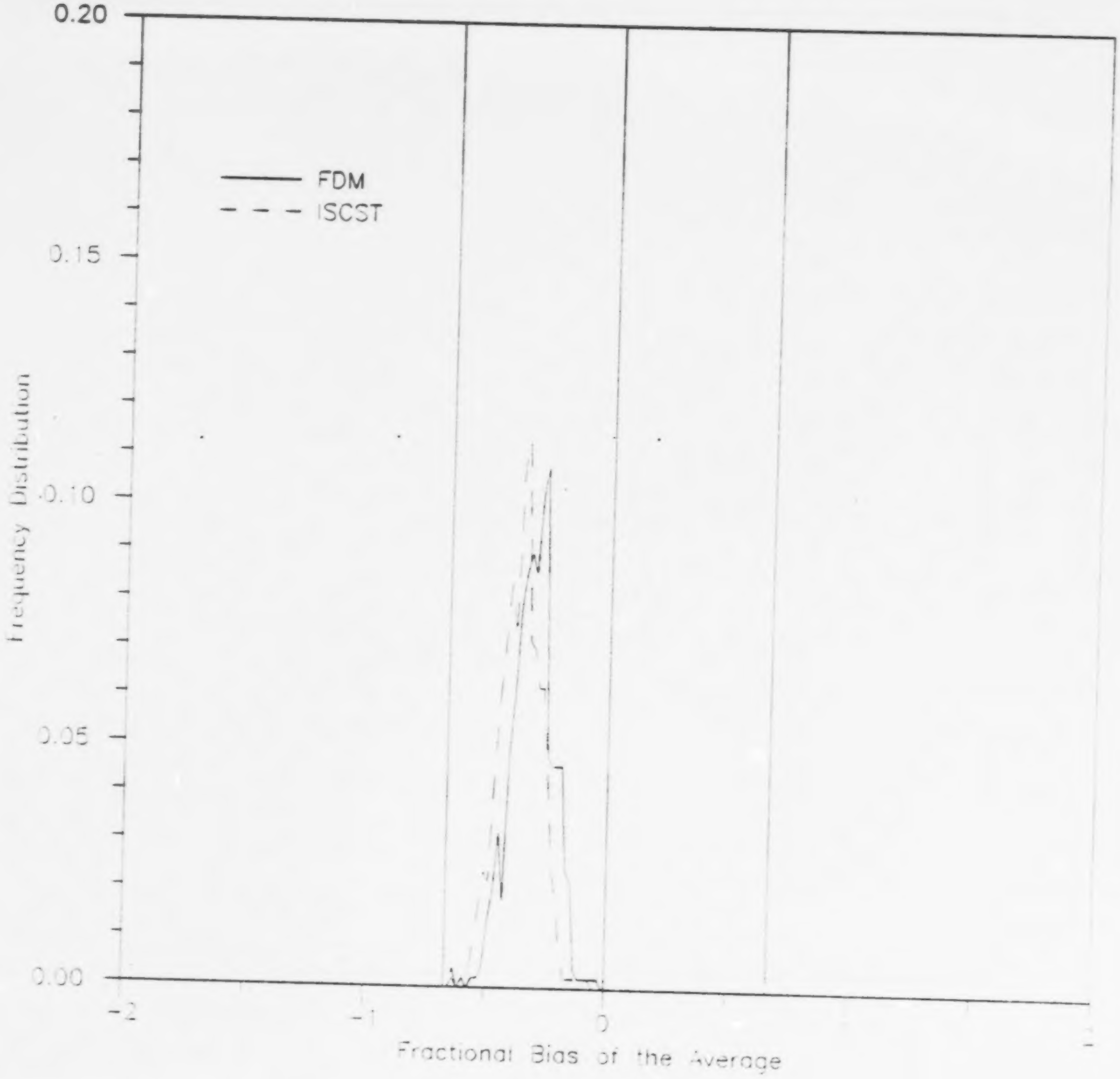


Figure 3-4. Fractional Bias Distributions for Single Tracer Experiments

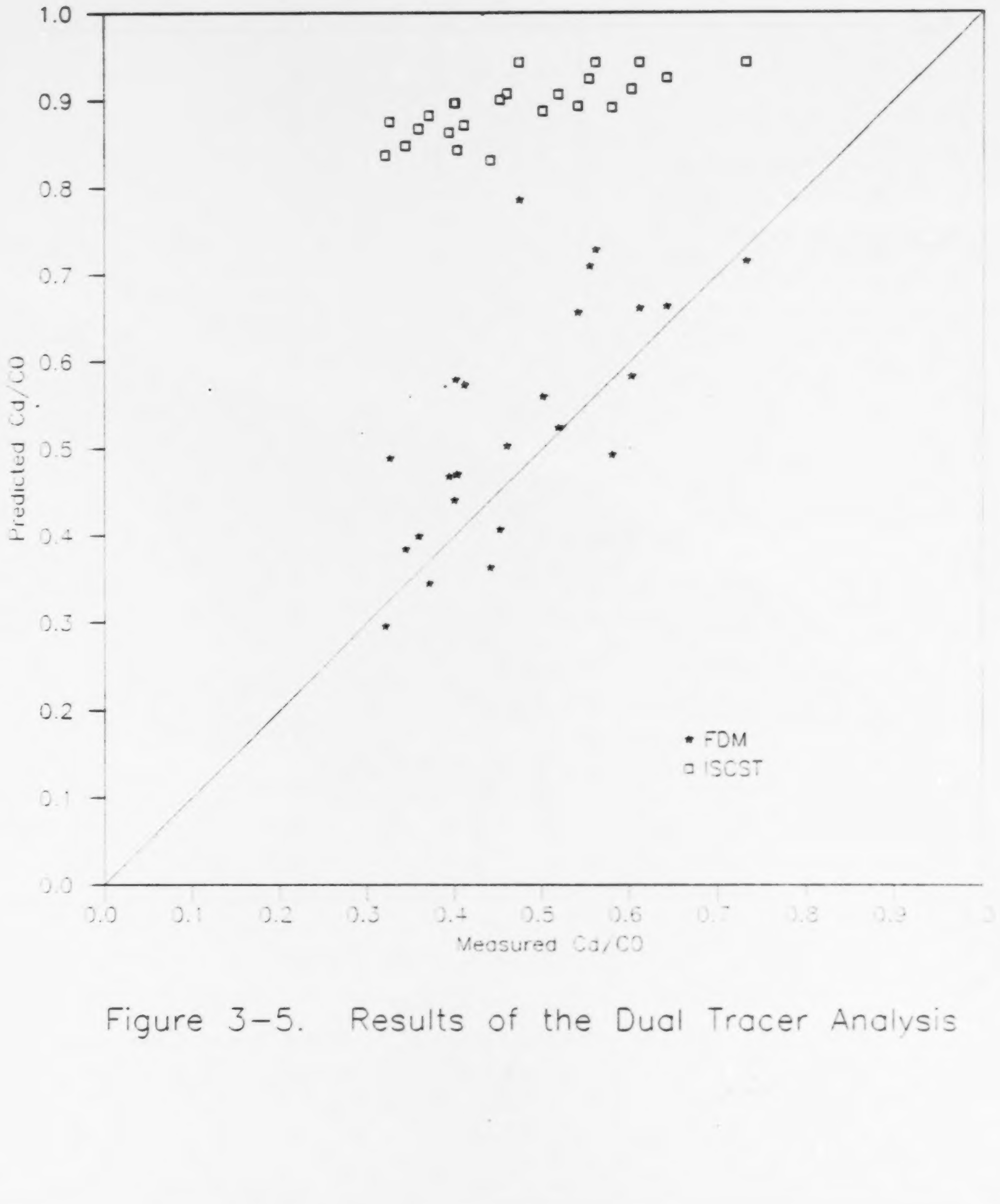


Figure 3-5. Results of the Dual Tracer Analysis

the figure that FDM outperforms ISCST in this comparison significantly. The ISCST data show virtually no deposition, while the measured and FDM data clearly shown significant deposition was occurring. There were too few values here to conduct a significant statistical analysis, but it can safely be concluded based on Figure 3-5 that FDM performed better in the dual tracer experiments than the ISC model.

4.0 CONCLUSIONS

Both the FDM and the ISCST Model were evaluated using the Hanford 67 data base. In all cases the FDM performed better than the ISCST Model. For the dual tracer experimental data, the FDM performed significantly better than ISCST, however, for the single tracer experiments, it is uncertain whether FDM's performance was statistically better than ISCST.

The reasons for the apparent discrepancy in performance between these two data set evaluations are not fully understood. One possible explanation is that for the dual tracer experiments, deposition velocity and gravitational settling velocity were provided, rather than the internal calculation of these parameters by the FDM.

The results of the single tracer experiments, however, do not cloud the issue of FDM versus ISCST performance in the overall data comparisons. Through 3 full validation exercises comparing the FDM and ISC models, in every case the FDM outperformed the ISCST model. Some of the results are more statistically significant than others, but the overall pattern is clear, that FDM, with its superior treatment of deposition, is a better predictor of concentration than ISC for problems involving particulate deposition.

REFERENCES

Cole, C. F. 1988. "A Performance Evaluation of the EPA's ISC Model", Prepared for the American Mining Congress, TRC Environmental Consultants, Englewood, Colorado, TRC Project Number 4757-R12, September.

Cox, W. M. 1988. "Protocol for Determining the Best Performing Model", U. S. Environmental Protection Agency Report, August.

APPENDIX B

SAMPLE INPUT AND OUTPUT STREAMS

Sample Input Stream

```
TEST CASE
 1 1 2 1 1 1 1 1 1 2 1
   56   10    5   24
 60.        1.         1.         2.5
1.25       3.75       7.5        12.5       20.
0.0262     0.0678     0.1704     0.1536     0.5820
525.       1300.
255.       1530.
389.       1294.
443.       1136.
596.       388.
622.       1103.
824.       3191.
1344.      1939.
1554.      183.
61.        2365.
 10.535500E-02  0.00      610.0     1363.0       0.0       0.0
 10.680000E-01  1.00      610.0     1363.0       0.0       0.0
 10.119000E+00  1.00      549.0     1426.0       0.0       0.0
 10.102000E-01  1.00      488.0     1451.0       0.0       0.0
 30.330014E-04  0.00     1055.0     1512.0     354.0     305.0
 30.337000E-08  3.00     1055.0     1512.0     354.0     305.0
 30.330014E-04  0.00     1203.0     1256.0     149.0     217.0
 30.337000E-08  3.00     1203.0     1256.0     149.0     217.0
 30.288462E-06  0.00      237.0     1789.0     208.0     140.0
 30.337000E-08  3.00      237.0     1789.0     208.0     140.0
 30.201972E-05  0.00      513.0     1780.0     207.0     219.0
 30.337000E-08  3.00      513.0     1780.0     207.0     219.0
 30.124000E-03  0.00      683.0     1353.0      84.0      50.0
 30.337000E-08  3.00      683.0     1353.0      84.0      50.0
 30.413772E-05  0.00      318.0     1158.0      87.0      82.0
 30.337000E-08  3.00      318.0     1158.0      87.0      82.0
 30.413772E-05  0.00      549.0      795.0     149.0     122.0
 30.337000E-08  3.00      549.0      795.0     149.0     122.0
 30.413772E-05  0.00      195.0     1075.0     195.0     104.0
 30.337000E-08  3.00      195.0     1075.0     195.0     104.0
 30.413772E-05  0.00      402.0      597.0      85.0      85.0
 30.337000E-08  3.00      402.0      597.0      85.0      85.0
 30.413772E-05  0.00      299.0      634.0      85.0     195.0
 30.337000E-08  3.00      299.0      634.0      85.0     195.0
 30.413772E-05  0.00      610.0      207.0     140.0     146.0
 30.337000E-08  3.00      610.0      207.0     140.0     146.0
 20.622494E-03  0.00      999.7     1658.1     999.7    1475.2          30.0
 20.622494E-03  0.00     1146.0     1475.2     999.7    1475.2          30.0
 20.124499E-02  0.00      999.7     1475.2     816.9    1341.1          30.0
 20.674828E-03  0.00      816.9     1341.1     755.9    1414.3          30.0
 20.192808E-04  0.00      755.9     1414.3     694.9    1426.5          30.0
 20.192808E-04  0.00      694.9     1426.5     621.8    1365.5          30.0
 20.207957E-03  0.00      621.8     1365.5     658.4    1304.5          30.0
 20.110176E-03  0.00      658.4     1304.5     816.9    1341.1          30.0
 20.655547E-03  0.00      755.9     1414.3     719.3    1511.8          30.0
 20.655547E-03  0.00      719.3     1511.8     719.3    1670.3          30.0
```

```
20.655547E-03  0.00      719.3    1670.3      634.0    1914.1          30.0
20.655547E-03  0.00      634.0    1914.1      560.8    1962.9          30.0
20.550880E-04  0.00      560.8    1962.9      353.6    1828.8          30.0
20.275440E-04  0.00      353.6    1828.8      182.9    1828.8          30.0
20.275440E-04  0.00      353.6    1828.8      195.1    1731.3          30.0
20.200152E-03  0.00      585.2    1950.7      414.5    1731.3          30.0
20.200152E-03  0.00      609.6    1938.5      487.7    1743.5          30.0
20.200152E-03  0.00      621.8    1926.3      560.8    1743.5          30.0
20.454476E-03  0.00      816.9    1341.1      560.8    1170.4          30.0
20.454476E-03  0.00      560.8    1170.4      438.9    1146.0          30.0
20.454476E-03  0.00      438.9    1146.0      402.3    1109.5          30.0
20.134000E-03  0.00      402.3    1109.5      317.0    1158.2          30.0
20.454476E-03  0.00      402.3    1109.5      512.1     841.2          30.0
20.227238E-03  0.00      512.1     841.2      573.0     792.5          30.0
20.227238E-03  0.00      512.1     841.2      256.0    1036.3          30.0
20.227238E-03  0.00      512.1     841.2      463.3     804.7          30.0
20.227238E-03  0.00      463.3     804.7       85.3    1036.3          30.0
20.227238E-03  0.00       85.3    1036.3       61.0     963.2          30.0
20.227238E-03  0.00       61.0     963.2      597.4     182.9          30.0
20.227238E-03  0.00      207.3     755.9      426.7     573.0          30.0
     1.64     215.5    6         10000.0      286.0
     1.84     189.1    5         10000.0      285.3
     1.00     166.5    6         10000.0      284.7
     2.23     110.5    5         10000.0      284.0
     1.07      97.1    6         10000.0      283.4
     1.00      78.1    6         10000.0      283.4
     1.00     270.9    1          1400.0      283.0
     1.00     273.7    1          1400.0      283.0
     1.19      46.7    4           400.0      284.5
     1.00      85.1    1          1400.0      286.6
     1.35     185.1    2          1200.0      288.0
     1.87     188.8    2          1200.0      289.6
     1.96     194.5    1          1400.0      291.2
     2.63     211.6    1          1400.0      292.1
     3.02     195.2    2          1200.0      292.8
     3.03     173.2    2          1200.0      293.3
     2.01     213.2    1          1400.0      294.3
     2.54     197.7    1          1400.0      293.4
     1.96     179.4    1          1400.0      291.7
     1.76     217.7    1          1400.0      290.0
     1.01     125.4    6         10000.0      289.2
     1.00      50.6    6         10000.0      288.4
     1.19      53.6    4           400.0      288.0
     1.03      37.1    5         10000.0      287.4
```

Sample Output Stream

```
               FUGITIVE DUST MODEL (FDM)
               VERSION 90121
               MAY, 1990

RUN TITLE:
     TEST CASE

     INPUT FILE NAME:  test.IN
     OUTPUT FILE NAME:  test.OUT
     PLOT OUTPUT WRITTEN TO FILE NAME:  test.DAT

     CONVERGENCE OPTION 1=OFF, 2=ON                    1
     MET OPTION SWITCH, 1=CARDS, 2=PREPROCESSED        1
     PLOT FILE OUTPUT, 1=NO, 2=YES                     2
     MET DATA PRINT SWITCH, 1=NO, 2=YES                1
     POST-PROCESSOR OUTPUT, 1=NO, 2=YES                1
     DEP. VEL./GRAV. SETL. VEL., 1=DEFAULT, 2=USER     1
     PRINT 1-HOUR AVERAGE CONCEN, 1=NO, 2=YES          1
     PRINT 3-HOUR AVERAGE CONCEN, 1=NO, 2=YES          1
     PRINT 8-HOUR AVERAGE CONCEN, 1=NO, 2=YES          1
     PRINT 24-HOUR AVERAGE CONCEN, 1=NO, 2=YES         2
     PRINT LONG-TERM AVERAGE CONCEN, 1=NO, 2=YES       1
     NUMBER OF SOURCES PROCESSED                      56
     NUMBER OF RECEPTORS PROCESSED                    10
     NUMBER OF PARTICLE SIZE CLASSES                   5
     NUMBER OF HOURS OF MET DATA PROCESSED            24
     LENGTH IN MINUTES OF 1-HOUR OF MET DATA         60.
     ROUGHNESS LENGTH IN CM                         1.00
     SCALING FACTOR FOR SOURCE AND RECPTORS       1.0000
     PARTICLE DENSITY IN G/CM**3                    2.50

     GENERAL PARTICLE SIZE CLASS INFORMATION

                               GRAV.             FRACTION
       PARTICLE      CHAR.  SETTLING DEPOSITION   IN EACH
           SIZE       DIA.  VELOCITY   VELOCITY      SIZE
          CLASS       (UM)   (M/SEC)    (M/SEC)     CLASS
          -----  ---------  --------  ---------- --------
              1  1.2500000        **         **    0.0262
              2  3.7500000        **         **    0.0678
              3  7.5000000        **         **    0.1704
              4 12.5000000        **         **    0.1536
              5 20.0000000        **         **    0.5820
     ----------
     ** COMPUTED BY FDM
```

```
               RECEPTOR COORDINATES (X,Y,Z)

   (   525.,   1300.,  0.) (   255.,   1530.,  0.) (   389.,   1294.,  0.)
   (   443.,   1136.,  0.) (   596.,    388.,  0.) (   622.,   1103.,  0.)
   (   824.,   3191.,  0.) (  1344.,   1939.,  0.) (  1554.,    183.,  0.)
   (    61.,   2365.,  0.) (
SOURCE INFORMATION

         ENTERED EMIS.       TOTAL
         RATE (G/SEC,     EMISSION   WIND
          G/SEC/M OR          RATE  SPEED      X1        Y1       X2        Y2  HEIGHT     WIDTH
TYPE     G/SEC/M**2)      (G/SEC)   FAC.     (M)       (M)      (M)       (M)     (M)       (M)
---- --------------- ---------- ------ ------- -------- ------- -------- ------- -------
   1     0.005355000    0.00536  0.000    610.     1363.      0.        0.    0.50     0.00
   1     0.068000000    0.06800  1.000    610.     1363.      0.        0.    0.50     0.00
   1     0.119000000    0.11900  1.000    549.     1426.      0.        0.    0.50     0.00
   1     0.010200000    0.01020  1.000    488.     1451.      0.        0.    0.50     0.00
   3     0.000033001    3.56316  0.000   1055.     1512.    354.      305.    0.50     0.00
   3     0.000000003    0.00036  3.000   1055.     1512.    354.      305.    0.50     0.00
   3     0.000033001    1.06703  0.000   1203.     1256.    149.      217.    0.50     0.00
   3     0.000000003    0.00011  3.000   1203.     1256.    149.      217.    0.50     0.00
   3     0.000000288    0.00840  0.000    237.     1789.    208.      140.    0.50     0.00
   3     0.000000003    0.00010  3.000    237.     1789.    208.      140.    0.50     0.00
   3     0.000002020    0.09156  0.000    513.     1780.    207.      219.    0.50     0.00
   3     0.000000003    0.00015  3.000    513.     1780.    207.      219.    0.50     0.00
   3     0.000124000    0.52080  0.000    683.     1353.     84.       50.    0.50     0.00
   3     0.000000003    0.00001  3.000    683.     1353.     84.       50.    0.50     0.00
   3     0.000004138    0.02952  0.000    318.     1158.     87.       82.    0.50     0.00
   3     0.000000003    0.00002  3.000    318.     1158.     87.       82.    0.50     0.00
   3     0.000004138    0.07522  0.000    549.      795.    149.      122.    0.50     0.00
   3     0.000000003    0.00006  3.000    549.      795.    149.      122.    0.50     0.00
   3     0.000004138    0.08391  0.000    195.     1075.    195.      104.    0.50     0.00
   3     0.000000003    0.00007  3.000    195.     1075.    195.      104.    0.50     0.00
   3     0.000004138    0.02990  0.000    402.      597.     85.       85.    0.50     0.00
   3     0.000000003    0.00002  3.000    402.      597.     85.       85.    0.50     0.00
   3     0.000004138    0.06858  0.000    299.      634.     85.      195.    0.50     0.00
   3     0.000000003    0.00006  3.000    299.      634.     85.      195.    0.50     0.00
   3     0.000004138    0.08458  0.000    610.      207.    140.      146.    0.50     0.00
   3     0.000000003    0.00007  3.000    610.      207.    140.      146.    0.50     0.00
   2     0.000622494    0.11385  0.000   1000.     1658.  -1000.     1475.    0.50    30.00
   2     0.000622494    0.09107  0.000   1146.     1475.   1000.     1475.    0.50    30.00
   2     0.001244990    0.28226  0.000   1000.     1475.    817.     1341.    0.50    30.00
   2     0.000674828    0.06430  0.000    817.     1341.    756.     1414.    0.50    30.00
   2     0.000019281    0.00120  0.000    756.     1414.    695.     1427.    0.50    30.00
   2     0.000019281    0.00184  0.000    695.     1427.    622.     1366.    0.50    30.00
   2     0.000207957    0.01479  0.000    622.     1366.    658.     1305.    0.50    30.00
   2     0.000110176    0.01792  0.000    658.     1305.    817.     1341.    0.50    30.00
   2     0.000655547    0.06827  0.000    756.     1414.    719.     1512.    0.50    30.00
   2     0.000655547    0.10390  0.000    719.     1512.    719.     1670.    0.50    30.00
   2     0.000655547    0.16932  0.000    719.     1670.    634.     1914.    0.50    30.00
   2     0.000655547    0.05767  0.000    634.     1914.    561.     1963.    0.50    30.00
   2     0.000055088    0.01360  0.000    561.     1963.    354.     1829.    0.50    30.00
   2     0.000027544    0.00470  0.000    354.     1829.    183.     1829.    0.50    30.00
   2     0.000027544    0.00513  0.000    354.     1829.    195.     1731.    0.50    30.00
   2     0.000200152    0.05564  0.000    585.     1951.    415.     1731.    0.50    30.00
   2     0.000200152    0.04603  0.000    610.     1939.    488.     1744.    0.50    30.00
   2     0.000200152    0.03857  0.000    622.     1926.    561.     1744.    0.50    30.00
   2     0.000454476    0.13988  0.000    817.     1341.    561.     1170.    0.50    30.00
   2     0.000454476    0.05650  0.000    561.     1170.    439.     1146.    0.50    30.00
   2     0.000454476    0.02349  0.000    439.     1146.    402.     1110.    0.50    30.00
   2     0.000134000    0.01316  0.000    402.     1110.    317.     1158.    0.50    30.00
   2     0.000454476    0.13175  0.000    402.     1110.    512.      841.    0.50    30.00
   2     0.000227238    0.01772  0.000    512.      841.    573.      793.    0.50    30.00
   2     0.000227238    0.07316  0.000    512.      841.    256.     1036.    0.50    30.00
   2     0.000227238    0.01385  0.000    512.      841.    463.      805.    0.50    30.00
   2     0.000227238    0.10074  0.000    463.      805.     85.     1036.    0.50    30.00
   2     0.000227238    0.01750  0.000     85.     1036.     61.      963.    0.50    30.00
   2     0.000227238    0.21517  0.000     61.      963.    597.      183.    0.50    30.00
   2     0.000227238    0.06491  0.000    207.      756.    427.      573.    0.50    30.00
                    ===========
TOTAL EMISSIONS         7.84414
NOTE:  SOME SOURCE EMISSION RATES ARE A FUNCTION OF WIND SPEED AND TOTAL IS NOT CORRECT
```

```
              24 HOUR AVERAGE FOR HOUR ENDING    24
                   CONCENTRATIONS IN MICROGRAMS/M**3

(   525.,   1300.,   122.035) (   255.,   1530.,    36.700) (   389.,   1294.,    79.491)
(   443.,   1136.,   300.847) (   596.,    388.,    12.260) (   622.,   1103.,    51.508)
(   824.,   3191.,     5.018) (  1344.,   1939.,    27.336) (  1554.,    183.,     0.042)
(    61.,   2365.,     3.985) (
          24 HOUR AVERAGE FOR HOUR ENDING    24
               DEPOSITION RATE IN MICROGRAMS/M**2/SEC

(   525.,   1300.,      1.242) (  255.,   1530.,      0.401) (   389.,   1294.,      0.688)
(   443.,   1136.,      5.512) (  596.,    388.,      0.181) (   622.,   1103.,      0.482)
(   824.,   3191.,      0.051) ( 1344.,   1939.,      0.383) (  1554.,    183.,      0.001)
(    61.,   2365.,      0.020) (
```

APPENDIX C

RELEVANT SECTIONS FROM THE CALINE3 USER'S GUIDE

5. MODEL DESCRIPTION

5.1 Gaussian Element Formulation

CALINE3 divides individual highway links into a series of elements from which incremental concentrations are computed and then summed to form a total concentration estimate for a particular receptor location (see Fig. 1). The receptor distance is measured along a perpendicular from the receptor to the highway centerline. The first element is formed at this point as a square with sides equal to the highway width. The lengths of subsequent elements are described by the following formula:

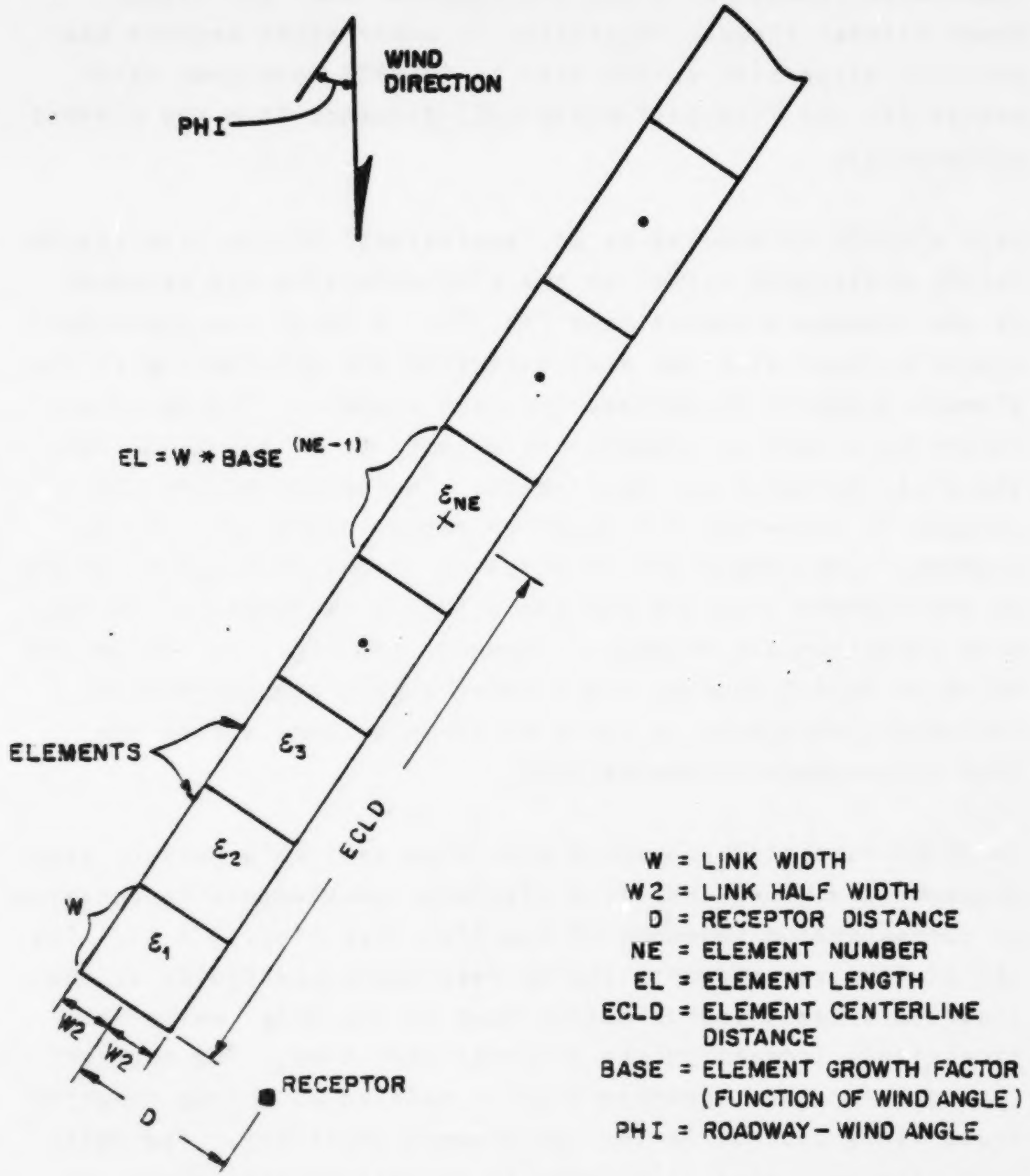
$$EL = W*BASE^{(NE-1)}$$

Where, EL = Element Length
W = Highway Width
NE = Element Number
BASE = Element Growth Factor

$PHI<20°$, $BASE=1.1$
$20° \leq PHI<50°$, $BASE=1.5$
$50° \leq PHI<70°$, $BASE=2.0$
$70° \leq PHI$, $BASE=4.0$

(Note: Capitalized variables shown in text and figures are identical to those used in the computer coding.)

Thus, as element resolution becomes less important with distance from the receptor, elements become larger to permit efficiency in computation. The choice of the element growth factor as a function of roadway-wind angle (PHI) range represents a good


WIND DIRECTION
PHI
EL = W * BASE $^{(NE-1)}$
ε_{NE}
ELEMENTS
ε_3
ε_2
ε_1
ECLD
W
W2
W2
D
RECEPTOR
W = LINK WIDTH
W2 = LINK HALF WIDTH
D = RECEPTOR DISTANCE
NE = ELEMENT NUMBER
EL = ELEMENT LENGTH
ECLD = ELEMENT CENTERLINE DISTANCE
BASE = ELEMENT GROWTH FACTOR (FUNCTION OF WIND ANGLE)
PHI = ROADWAY - WIND ANGLE

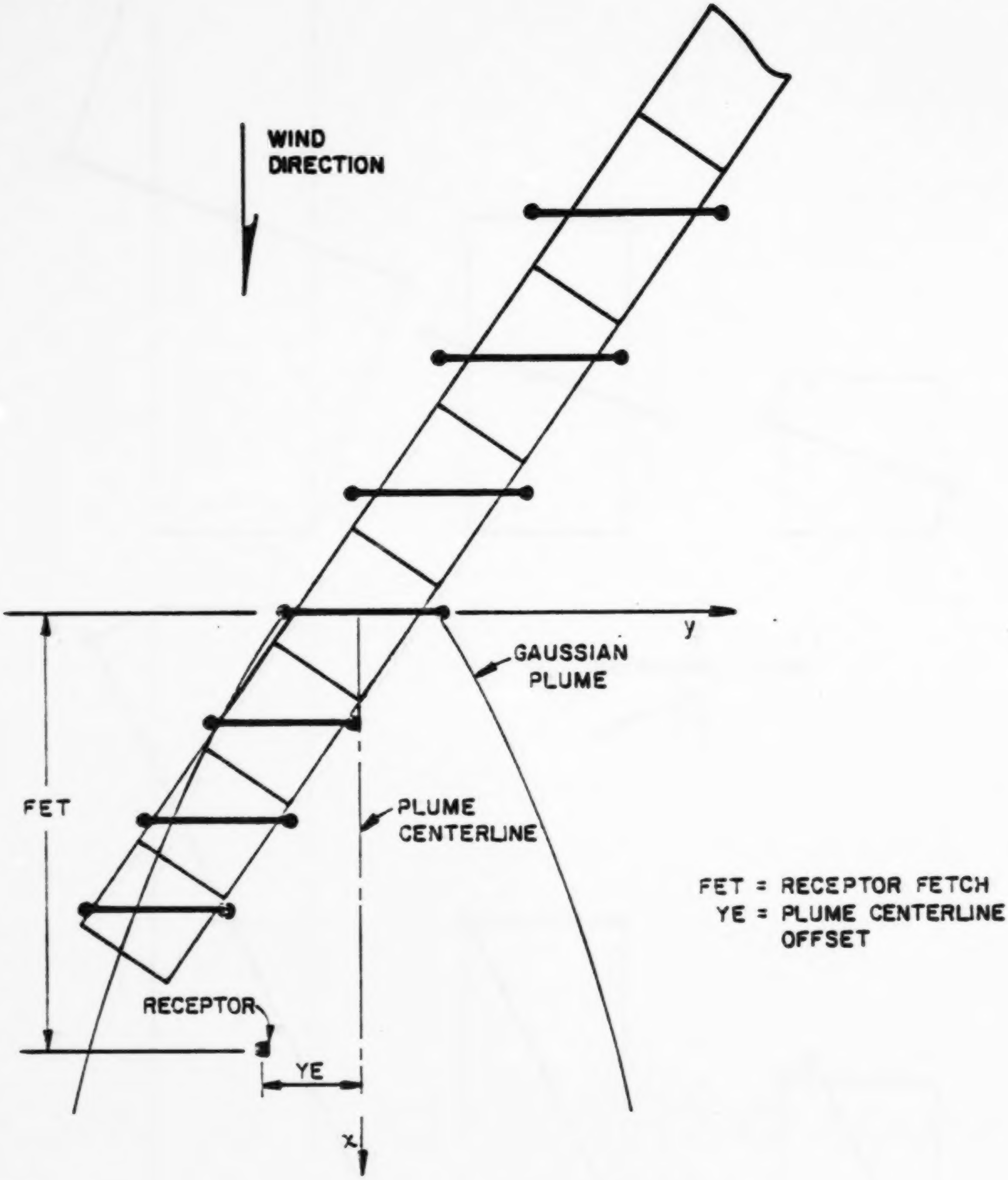
ELEMENT SERIES USED BY CALINE3

FIGURE 1

compromise between accuracy and computational efficiency. Finer initial element resolution is unwarranted because the vertical dispersion curves used by CALINE3 have been calibrated for the link half-width (W2) distance from the element centerpoint.

Each element is modeled as an "equivalent" finite line source (EFLS) positioned normal to the wind direction and centered at the element midpoint (see Fig. 2). A local x-y coordinate system aligned with the wind direction and originating at the element midpoint is defined for each element. The emissions occurring within an element are assumed to be released along the EFLS representing the element. The emissions are then assumed to disperse in a Gaussian manner downwind from the element. The length and orientation of the EFLS are functions of the element size and the angle (PHI,ϕ) between the average wind direction and highway alignment (see Fig. 3). Values of PHI=0 or PHI=90 degrees are altered within the program an insignificant amount to avoid division by zero during the EFLS trigonometric computations.

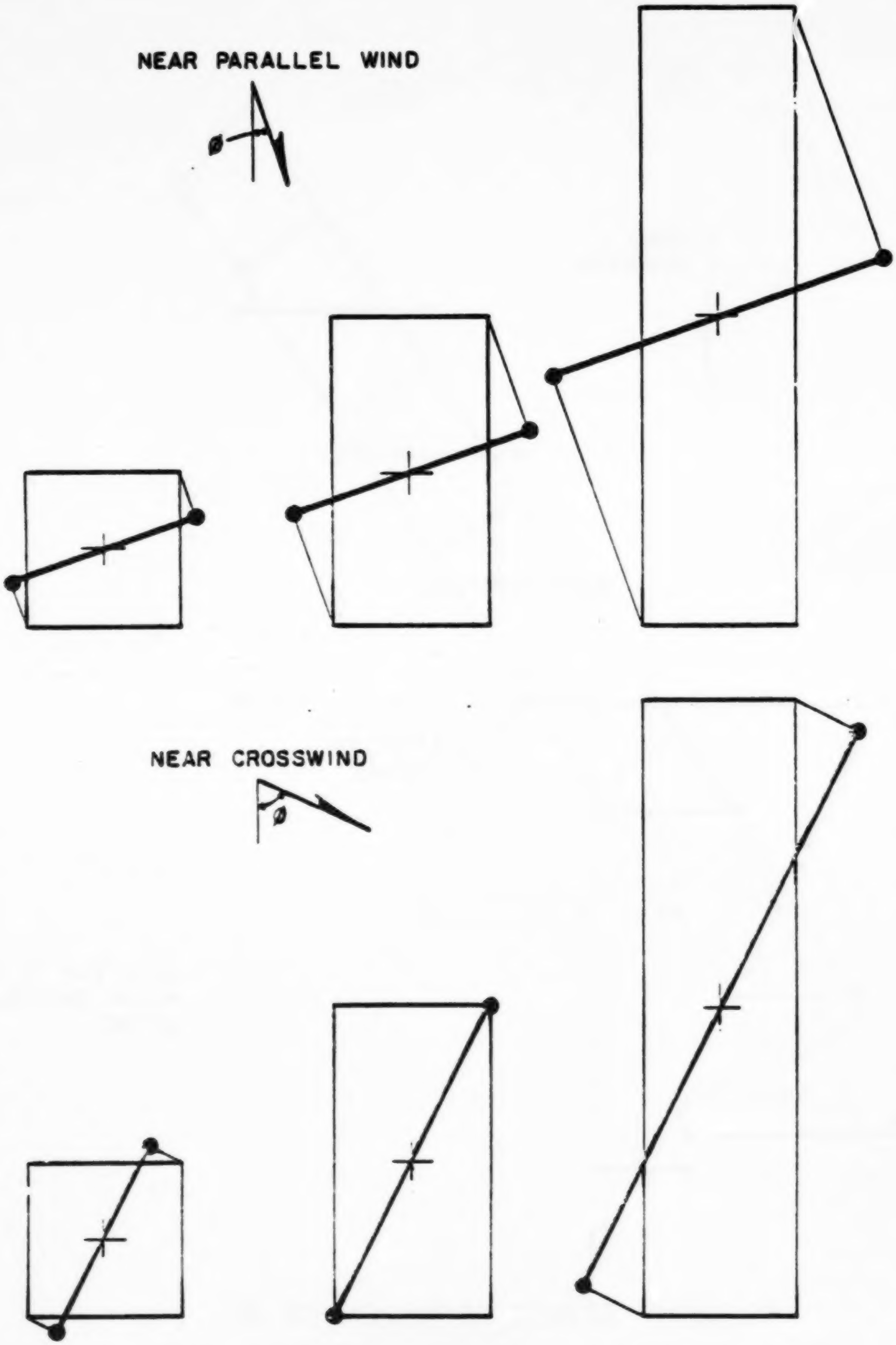
In order to distribute emissions in an equitable manner, each element is divided into five discrete sub-elements represented by corresponding segments of the EFLS (see Figs. 4 & 5). The use of five sub-elements yields reasonable continuity to the discrete element approximation used by the model while not excessively increasing the computational time. The source strength for the segmented EFLS is modeled as a step function whose value depends on the sub-element emissions. The emission rate/unit area is assumed to be uniform throughout the element for the purposes of computing this step function. The size and location of the sub-elements are a function of element size and wind angle (see Fig. 6).


WIND
DIRECTION
y
GAUSSIAN
PLUME
FET
PLUME
CENTERLINE
FET = RECEPTOR FETCH
YE = PLUME CENTERLINE
OFFSET
RECEPTOR
YE
x

ELEMENT SERIES REPRESENTED BY
SERIES OF EQUIVALENT FINITE LINE SOURCES

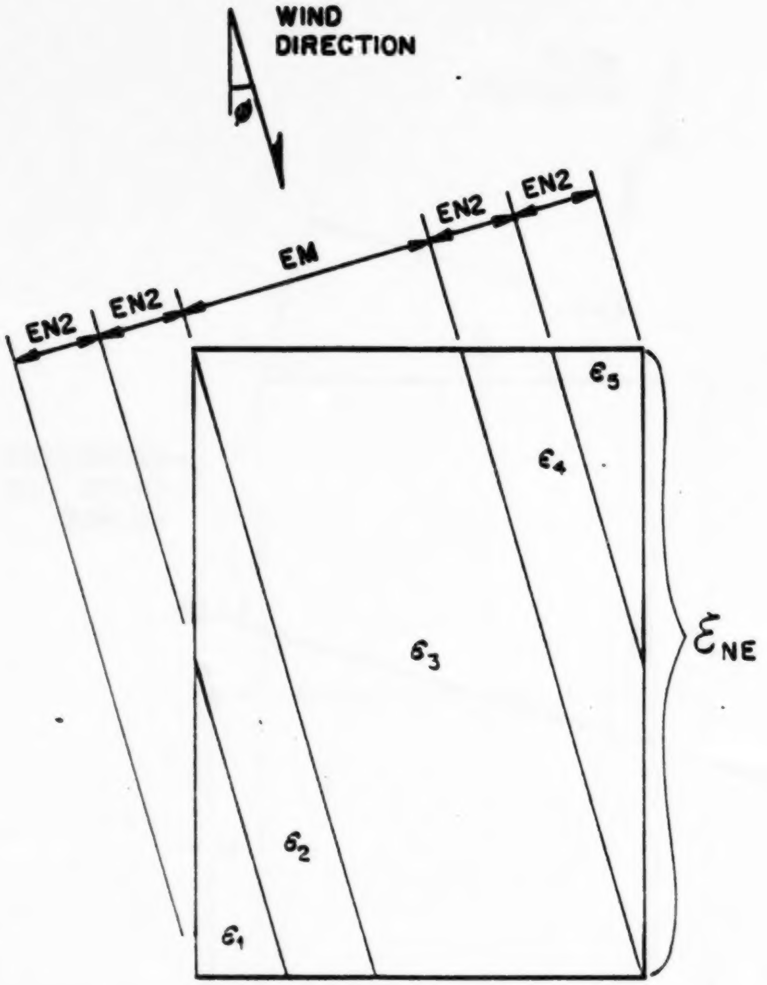
FIGURE 2

142


NEAR PARALLEL WIND
ø
NEAR CROSSWIND
ø

EQUIVALENT FINITE LINE SOURCE REPRESENTATION FOR VARIOUS ELEMENT SIZES AND WIND ANGLES

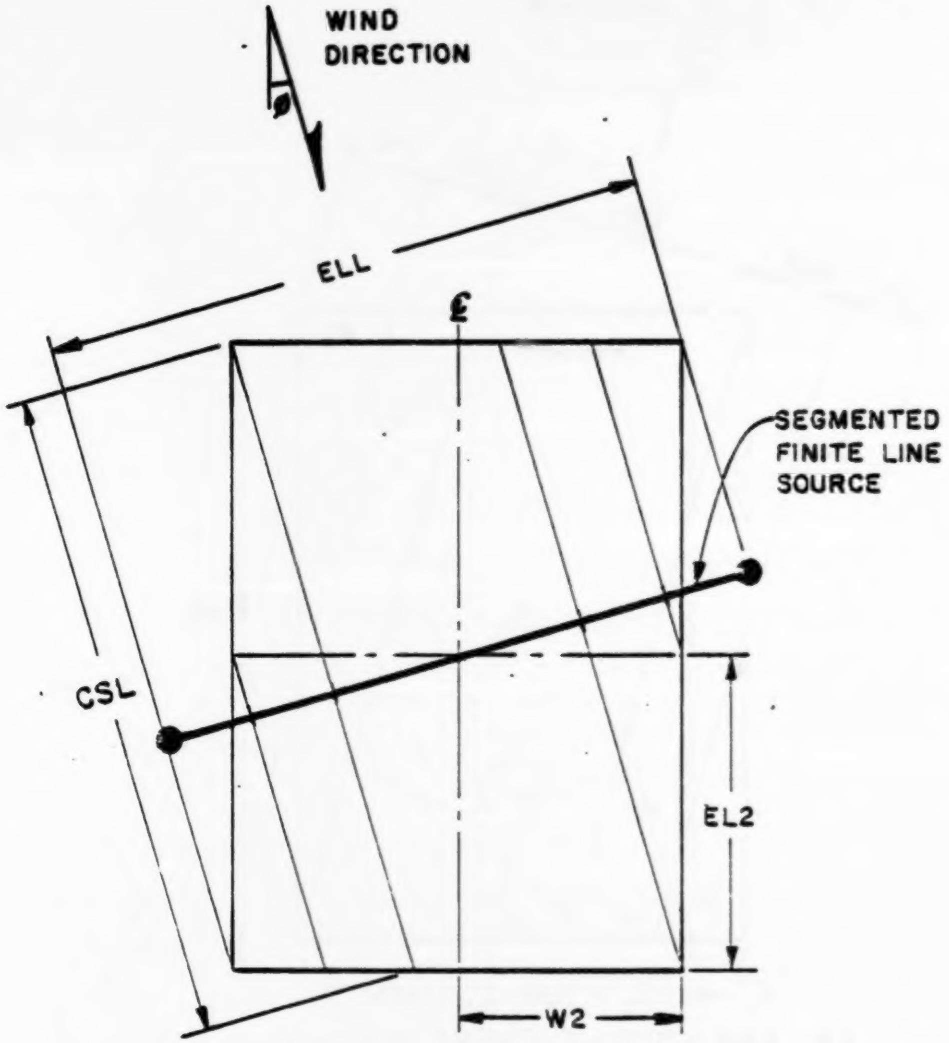
FIGURE 3


WIND DIRECTION
ϕ
EN2
EN2
EM
EN2
EN2
ϵ_5
ϵ_4
ϵ_3
ϵ_2
ϵ_1
$\mathcal{E}_{NE}$

$\epsilon_1 \rightarrow \epsilon_5$ = SUB-ELEMENTS
EM, EN2 = SUB-ELEMENT WIDTHS

CALINE3 SUB-ELEMENTS

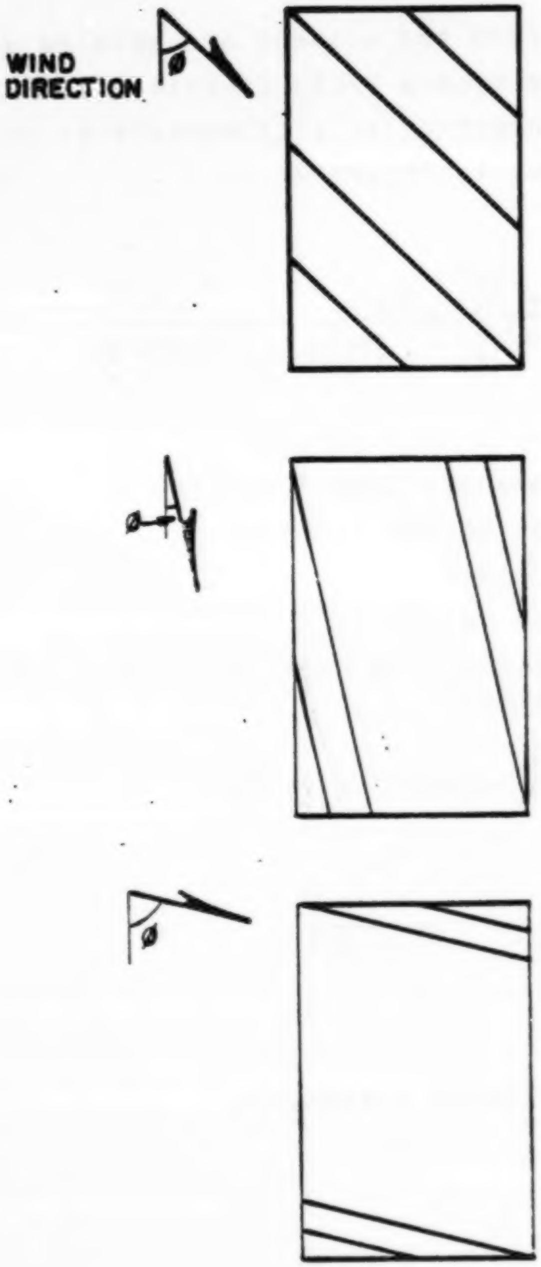
FIGURE 4


WIND DIRECTION
ø
ELL
℄
SEGMENTED FINITE LINE SOURCE
CSL
EL2
W2

ELL = EQUIVALENT LINE LENGTH
CSL = CENTRAL SUB-ELEMENT LENGTH

CALINE3 FINITE LINE SOURCE
ELEMENT REPRESENTATION

FIGURE 5


WIND DIRECTION
ø
ø
ø

SUB-ELEMENT CONSTRUCTION FOR VARIOUS WIND ANGLES

FIGURE 6

Downwind concentrations from the element are modeled using the crosswind finite line source (FLS) Gaussian formulation. Consider the receptor concentration attributable to an FLS segment of length dy shown in Figure 7:

$$dC = \frac{q\,dy}{2\pi u \sigma_y \sigma_z}\left[\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\right]\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right\}$$

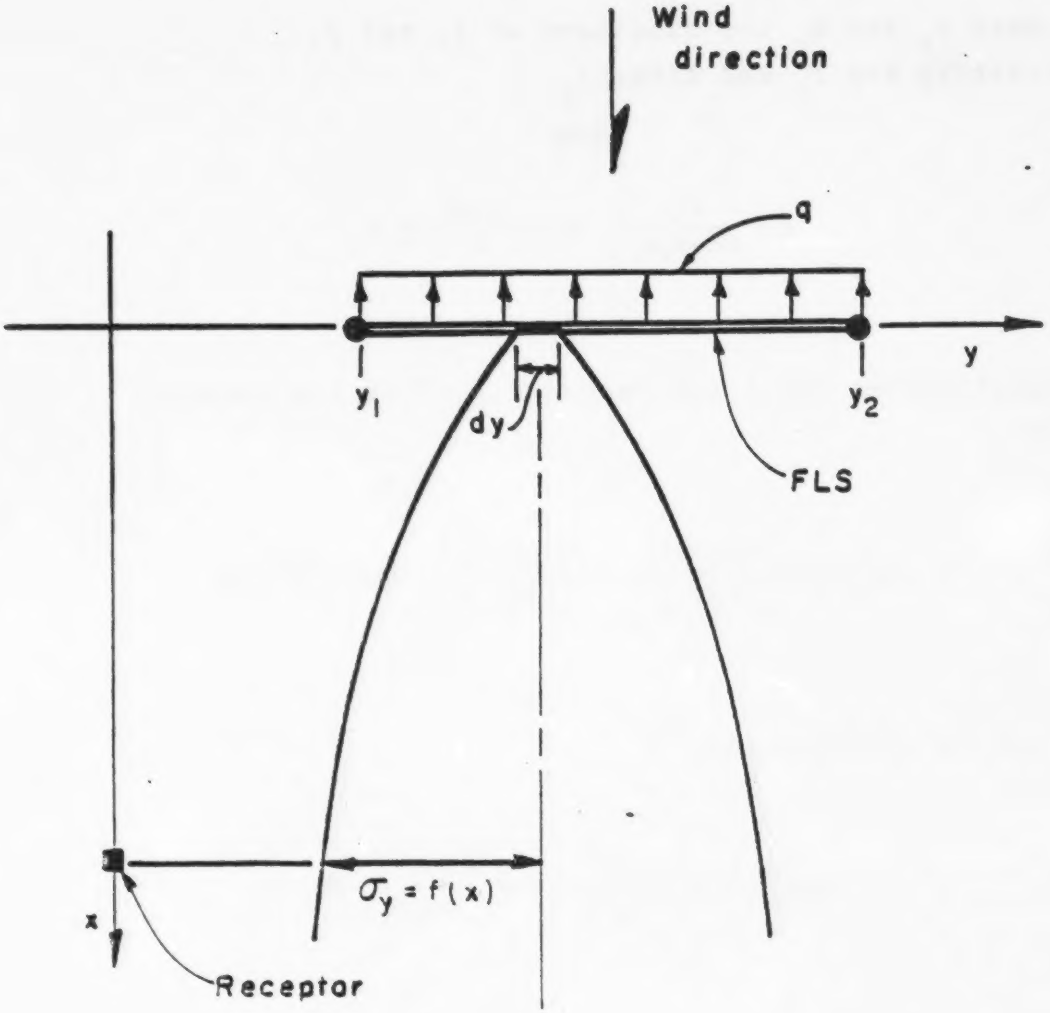
Where,
dC = Incremental Concentration
q = Lineal Source Strength
u = Wind Speed
H = Source Height
σ_y, σ_z = Horizontal and Vertical Dispersion Parameters

Since σ_z is constant with respect to y, let:

$$A = \exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]$$

Integrating over the FLS length yields:

$$C = \frac{Aq}{2\pi u \sigma_y \sigma_z}\int_{y_1}^{y_2} \exp\left(\frac{-y^2}{2\sigma_y^2}\right) dy$$


Wind direction
q
y
y_1
y_2
dy
FLS
$\sigma_y = f(x)$
x
Receptor

q = UNIFORM LINE SOURCE STRENGTH

σ_y = HORIZONTAL DISPERSION PARAMETER

GENERALIZED FINITE LINE SOURCE (FLS)

FIGURE 7

Note that σ_y and σ_z are functions of x, not y. Substituting $p=y/\sigma_y$ and $dp=dy/\sigma_y$:

$$C = \frac{Aq}{2\pi u\sigma_y\sigma_z}\int_{y_1/\sigma_y}^{y_2/\sigma_y} \exp\left(\frac{-p^2}{2}\right)\sigma_z\,dp$$

Backsubstituting for A and removing σ_y from the integral leaves:

$$C = \frac{q}{2\pi\sigma_z u}\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right\}\int_{y_1/\sigma_y}^{y_2/\sigma_y} \exp\left(\frac{-p^2}{2}\right)dp$$

This can be rewritten as:

$$C = \frac{q}{\sqrt{2\pi}\,\sigma_z u}\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right\}\cdot PD$$

Where,

$$PD = \frac{1}{\sqrt{2\pi}}\int_{y_1/\sigma_y}^{y_2/\sigma_y} \exp\left(\frac{-p^2}{2}\right)dp = \text{Normal Probability Density Function}$$

CALINE3 computes receptor concentrations by approximating the crosswind FLS equation in the following manner (see Fig. 8):

$$C = \frac{1}{\sqrt{2\pi}U} * \sum_{i=1}^{n} \left\{ \frac{1}{SGZ_i} * \sum_{k=-CNT}^{CNT} \left[\exp\left(\frac{-(Z-H+2*k*L)^2}{2*SGZ_i^{\,2}} \right) + \exp\left(\frac{-(Z+H+2*k*L)^2}{2*SGZ_i^{\,2}} \right) \right] * \sum_{j=1}^{5} (WT_j * QE_i * PD_{ij}) \right\}$$

Where,

n = Total number of elements

CNT = Number of multiple reflections required for convergence

U = Wind speed

L = Mixing height (MIXH in coding)

SGZ_i = σ_z as f(x) for ith element

QE_i = Central sub-element lineal source strength for ith element

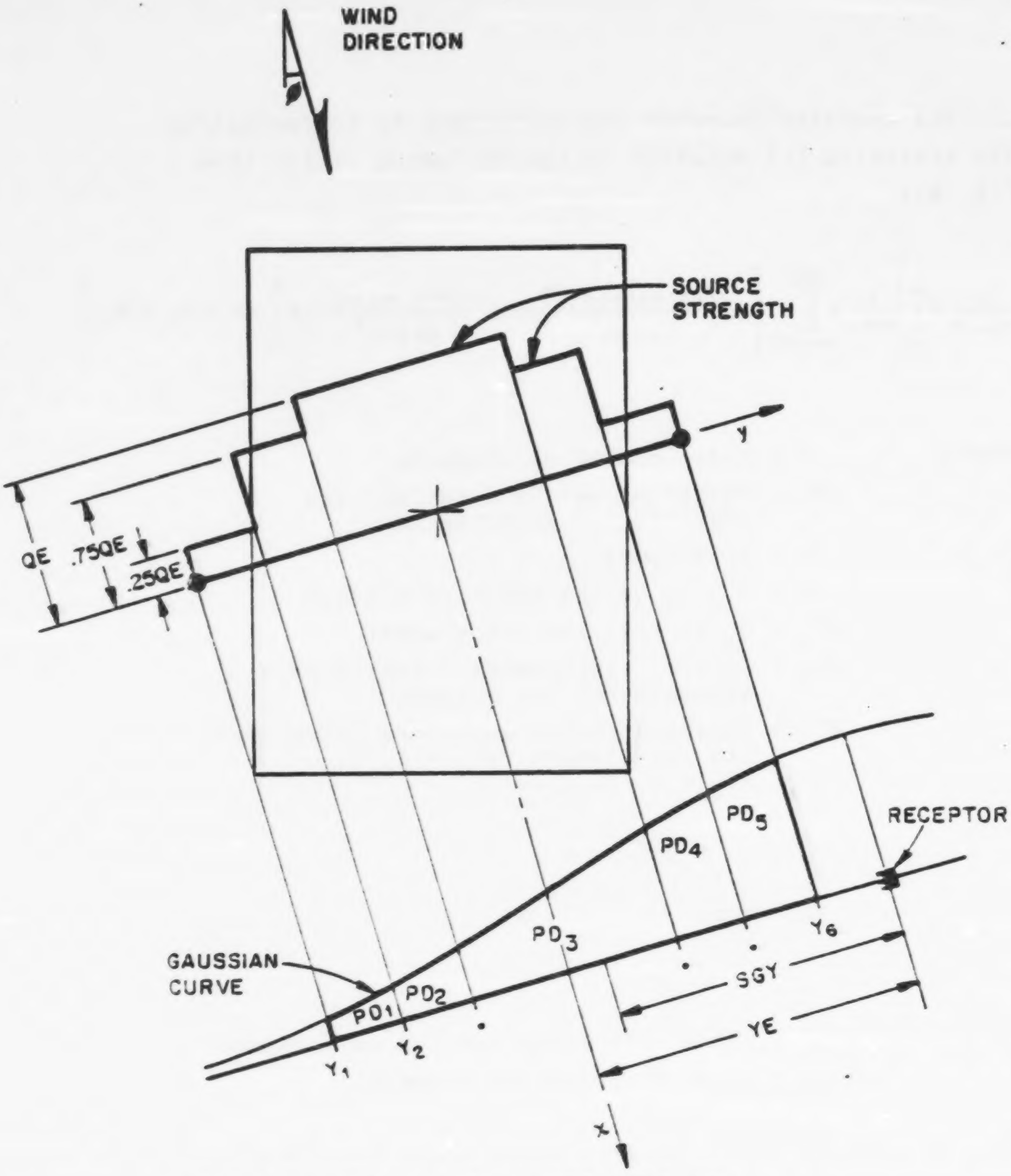
WT_j = Source strength weighting factor for jth sub-element ($WT_1 = 0.25$, $WT_2 = 0.75$, ...)

$$PD_{ij} = \frac{1}{\sqrt{2\pi}} \int_{Y_j/SGY_i}^{Y_{j+1}/SGY_i} \exp\left(\frac{-p^2}{2}\right) dp$$

Y_j, Y_{j+1} = Offset distances for jth sub-element

SGY_i = σ_y as f(x) for ith element

PD_{ij} is calculated by use of a fifth order polynomial approximation(9). Note the addition of multiple reflection terms represented by non-zero k indices to account for restricted mixing height (L).


WIND DIRECTION
SOURCE STRENGTH
y
QE
.75QE
.25QE
RECEPTOR
PD$_5$
PD$_4$
PD$_3$
PD$_2$
PD$_1$
GAUSSIAN CURVE
Y$_1$
Y$_2$
Y$_6$
SGY
YE
x

QE = EQUIVALENT LINE SOURCE STRENGTH
PD = PROBABILITY DENSITY
SGY = HORIZONTAL DISPERSION PARAMETER
YE = PLUME CENTERLINE OFFSET

CALINE3 INTEGRATED FINITE LINE SOURCE AND SUB-ELEMENT MODEL

FIGURE 8

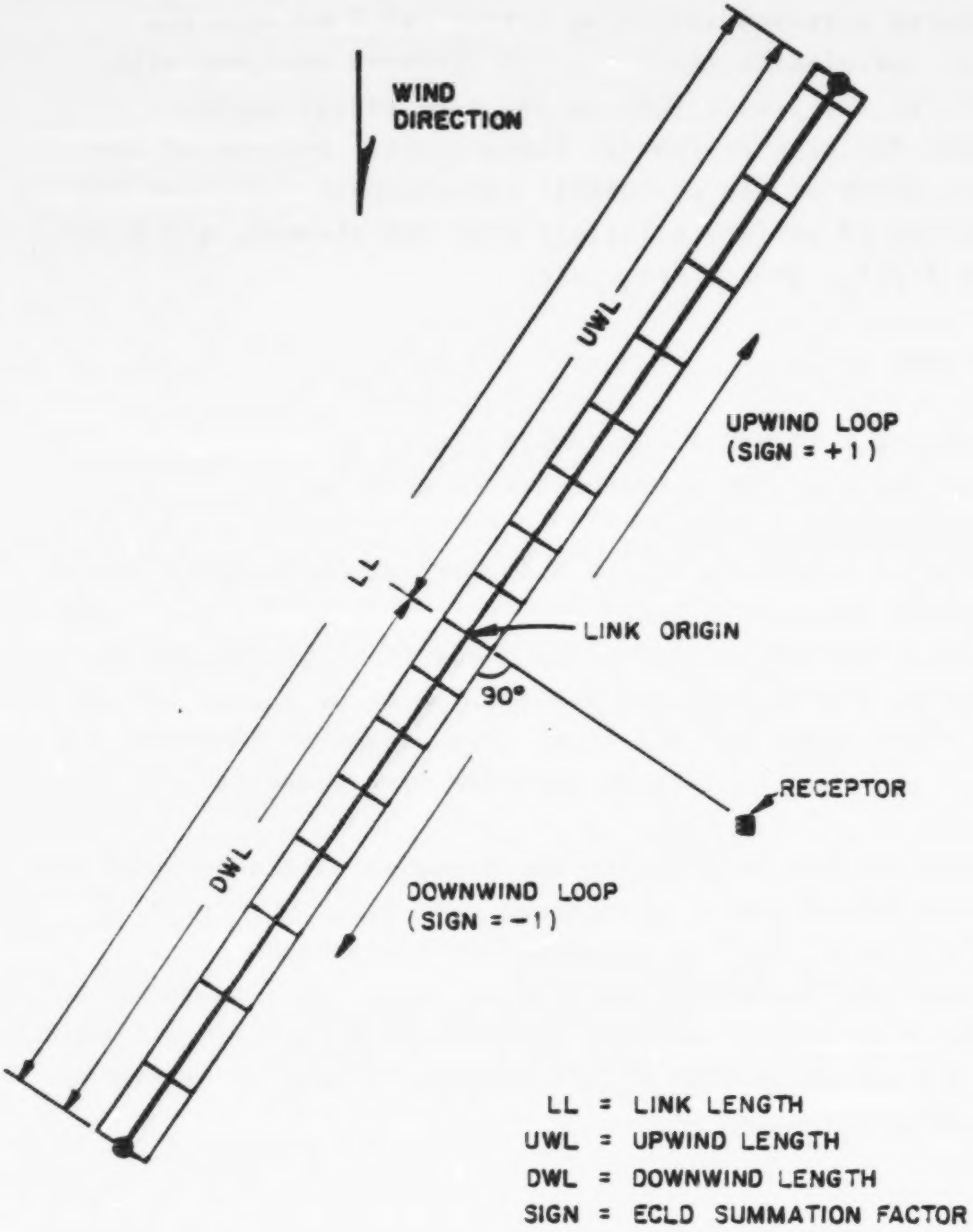
The source strength weighting factor (WT_j) adjusts the central sub-element lineal source strength measured with respect to the y-axis (QE) to the mean lineal source strength for each peripheral sub-element. Because of the uniform width of the peripheral sub-elements (EW2) and the assumption of uniform emissions over the element, q=0 @ $y=Y_1$, q=QE/2 @ $y=Y_2$, q=QE @ $y=Y_3$, etc.

Therefore,

$$WT_1 * QE = WT_5 * QE = (QE/2+0)/2 = 0.25\ QE$$
$$WT_2 * QE = WT_4 * QE = (QE+QE/2)/2 = 0.75\ QE$$

The element summation of the FLS equation is actually initiated twice for each highway link specified by the user (see Fig. 9). The computation takes place first in the upwind direction, ending when the element limits go beyond the upwind length (UWL) for the link. The length of the last element is modified to conform with the link endpoint.

The program then proceeds in the downwind direction until the downwind length (DWL) is exceeded. As soon as a negative value of fetch (FET) is encountered, the program automatically concludes the downwind loop computations. If a receptor is located within an element or downwind from part of an element, only the upwind portion of the element is used to determine the source strength.


WIND DIRECTION
UWL
UPWIND LOOP (SIGN = +1)
LL
LINK ORIGIN
90°
RECEPTOR
DWL
DOWNWIND LOOP (SIGN = −1)
LL = LINK LENGTH
UWL = UPWIND LENGTH
DWL = DOWNWIND LENGTH
SIGN = ECLD SUMMATION FACTOR

CALINE3 LINK - ELEMENT REPRESENTATION

FIGURE 9

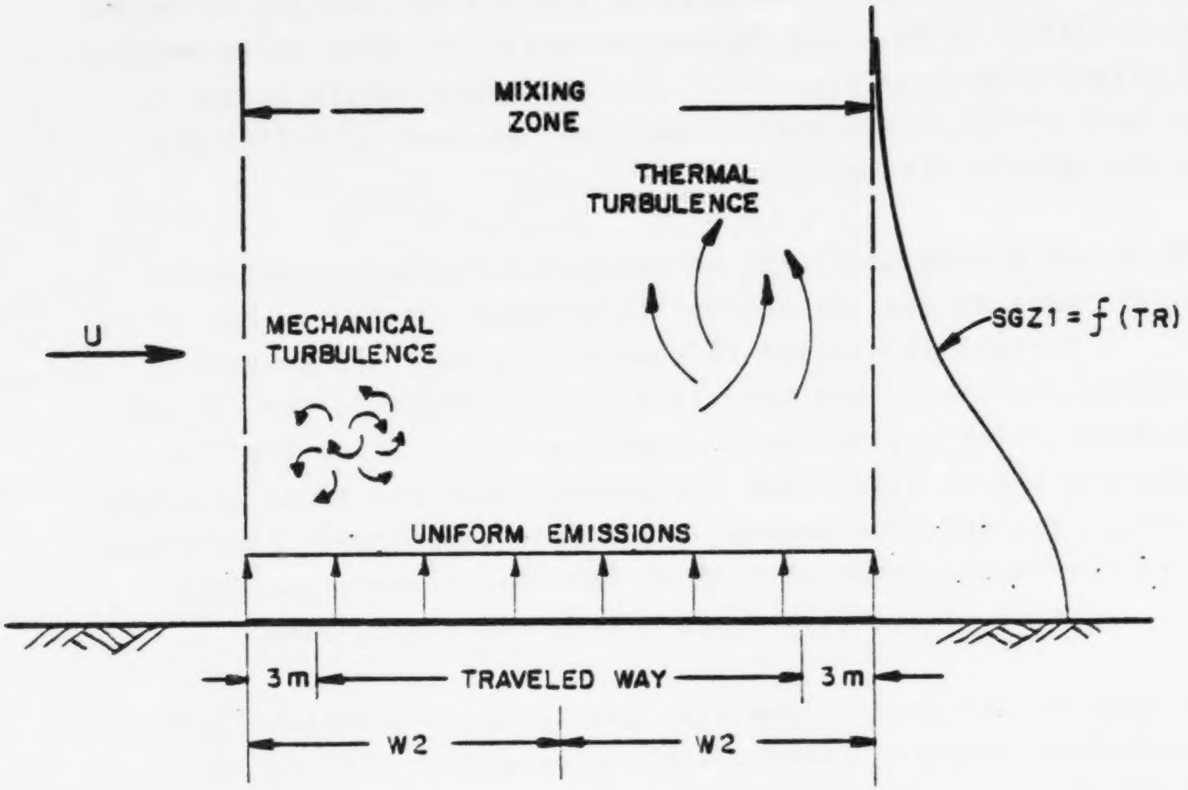
5.2 Mixing Zone Model

CALINE3 treats the region directly over the highway as a zone of uniform emissions and turbulence. This is designated as the mixing zone, and is defined as the region over the traveled way (traffic lanes - not including shoulders) plus three meters on either side (see Fig. 10). The additional width accounts for the initial horizontal dispersion imparted to pollutants by the vehicle wake effect.

Within the mixing zone, the mechanical turbulence created by moving vehicles and the thermal turbulence created by hot vehicle exhaust is assumed to predominate near the ground. Evidence indicates that this is a valid assumption for all but the most unstable atmospheric conditions(7). Since traffic emissions are released near the ground level and model accuracy is most important for neutral and stable atmospheric conditions, it is reasonable to model initial vertical dispersion (SGZ1) as a function of the turbulence within the mixing zone.

Analyses by Caltrans of the Stanford Research Institute(10) and General Motors(4) data bases indicate that SGZ1 is insensitive to changes in traffic volume and speed within the ranges of 4,000 to 8,000 vehicles/hr and 30 to 60 mph(7).

This may be due in part to the offsetting effects of traffic speed and volume. Higher volumes increase thermal turbulence but reduce traffic speed, thus reducing mechanical turbulence. For the range of traffic conditions cited, mixing zone turbulence may be considered a constant. However, pollutant residence time within the mixing zone, as dictated by the wind speed, significantly affects the amount of vertical


MIXING ZONE
THERMAL TURBULENCE
U
MECHANICAL TURBULENCE
SGZ1 = f (TR)
UNIFORM EMISSIONS
3 m
TRAVELED WAY
3 m
W2
W2

SGZ1 = INITIAL VERTICAL DISPERSION PARAMETER
TR = MIXING ZONE RESIDENCE TIME

CALINE3 MIXING ZONE

FIGURE 10

mixing that takes place within the zone. A distinct linear relationship between SGZ1 and residence time was exhibited by the two data bases studied.

CALINE3 arbitrarily defines mixing zone residence time as:

$$TR = W2/U$$

Where, W2 = Highway half-width
U = Wind speed

This definition is independent of wind angle and element size. It essentially provides a way of making the EFLS model compatible with the actual two-dimensional emissions release within an element. For oblique winds and larger elements, the plume is assumed to be sufficiently dispersed after traveling a distance of W2 such that the mixing zone turbulence no longer predominates.

The equation used by CALINE3 to relate SGZ1 to TR is:

$$\underset{(m)}{SGZ1} = 1.8 + 0.11 * \underset{(secs.)}{TR}$$

This was derived from the General Motors Data Base. It is adjusted in the model for averaging times other than 30 minutes by the following power law(11):

$$SGZ1_{ATIM} = SGZ1_{30} * (ATIM/30)^{0.2}$$

Where, ATIM = Averaging time (minutes)

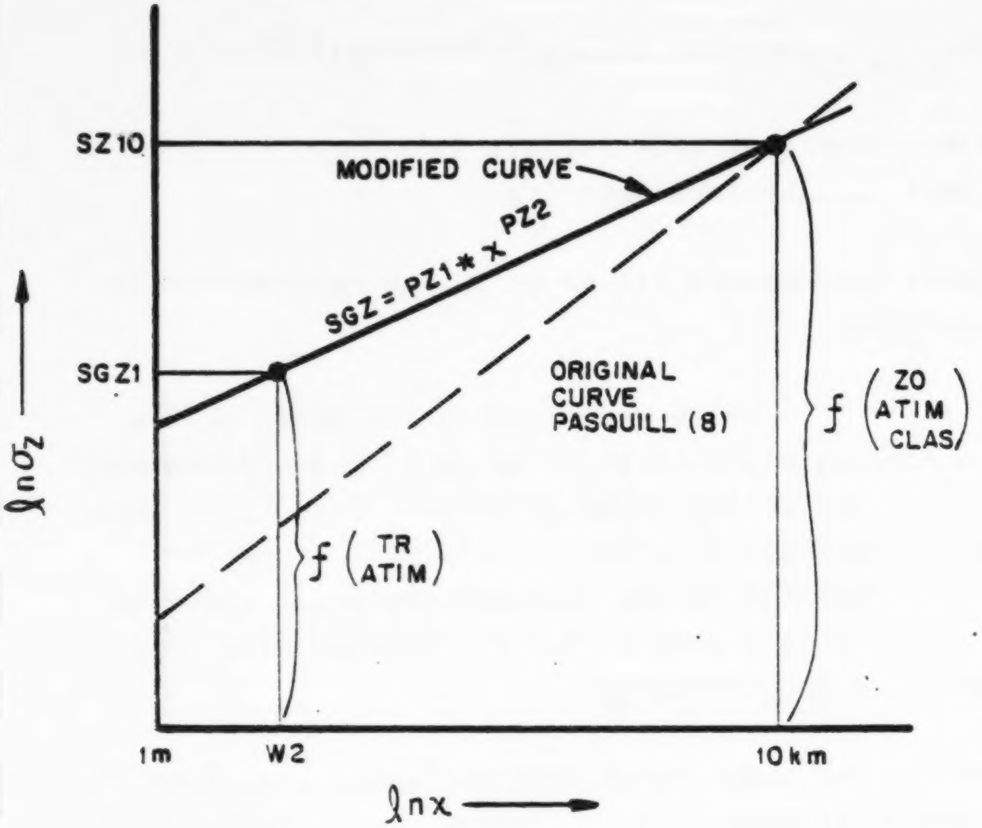
The value of SGZ1 is considered by CALINE3 to be independent of surface roughness and atmospheric stability class. The

user should note that SGZ1 accounts for all the enhanced dispersion over and immediately downwind of the roadway. Thus, the stability class used to run the model should be representative of the upwind or ambient stability without any additional modifications for traffic turbulence.

5.3 Vertical Dispersion Curves

The vertical dispersion curves used by CALINE3 are formed by using the value of SGZ1 from the mixing zone model, and the value of σ_z at 10 kilometers (SZ10) as defined by Pasquill(8). In effect, the power curve approximation suggested by Pasquill is elevated near the highway by the intense mixing zone turbulence (see Fig. 11). The significance of this added turbulence to plume growth lessens with increased distance from the source, though, in theory, it will never disappear. Extrapolated σ_z curves measured out to distances of 150 meters from the highway centerline under stable conditions for both the GM and SRI data bases intersect the Pasquill curves at roughly 10 kilometers. Beyond this point the power curve approximation to the true Pasquill curve, which is actually concave to the ℓnx axis, becomes increasingly inaccurate. Thus, the model should not be used for distances greater than 10 kilometers. As will be seen in the sensitivity analysis, contributions from elements greater than 10 kilometers from the receptor are insignificant even under the most stable atmospheric conditions.

For a given set of meteorological conditions, surface roughness (Z0) and averaging time (ATIM), CALINE3 uses the same vertical dispersion curve for each element within a highway link. This is possible since SGZ1 is always defined as occurring at a


SZ10
MODIFIED CURVE
SGZ = PZ1 * X PZ2
SGZ1
ORIGINAL CURVE PASQUILL (8)
f (ZO ATIM CLAS)
f (TR ATIM)
ℓnσz
1m
W2
10km
ℓnx

ZO = AERODYNAMIC ROUGHNESS
ATIM = AVERAGING TIME
CLAS = STABILITY CLASS
TR = MIXING ZONE RESIDENCE TIME
x = PLUME CENTERLINE AXIS
σ_Z = VERTICAL DISPERSION PARAMETER

MODIFIED VERTICAL DISPERSION CURVE — CALINE3

FIGURE 11

distance W2 downwind from the element centerpoint. SZ10 is adjusted for Z0 and ATIM by the following power law factors(11):

$$SZ10_{ATIM,Z0} = SZ10*(ATIM/3)^{0.2}*(Z0/10)^{0.07}$$

Where, ATIM = Averaging time (minutes)
Z0 = Surface roughness (cm)

Table 1 contains recommended values of Z0 for representative land use types(12).

The vertical dispersion of CO predicted by the model can be confined to a shallow mixed layer by means of the conventional Gaussian multiple reflection formulation(6). This capability was included in the model to allow for analysis of low traffic flow situations occurring during extended nocturnal low level inversions. Surprisingly high 8 hour CO averages have been measured under such conditions(13).

It is recommended for these cases that reliable, site specific field measurements be made. The following mixing height model proposed by Benkley and Schulman(14) can then be used:

$$MIXH = \frac{0.185*U*k}{\ln(Z/Z0)*f}$$

Where, U = Wind speed (m/s)
Z = Height U measured at (m)
Z0 = Surface roughness (m)
k = von Karman constant (0.35)
f = Coriolis parameter
= $1.45 \times 10^{-4} \cos\Theta$ (radians/sec)
Θ = 90° - site latitude

TABLE 1

Surface Roughness for Various Land Uses

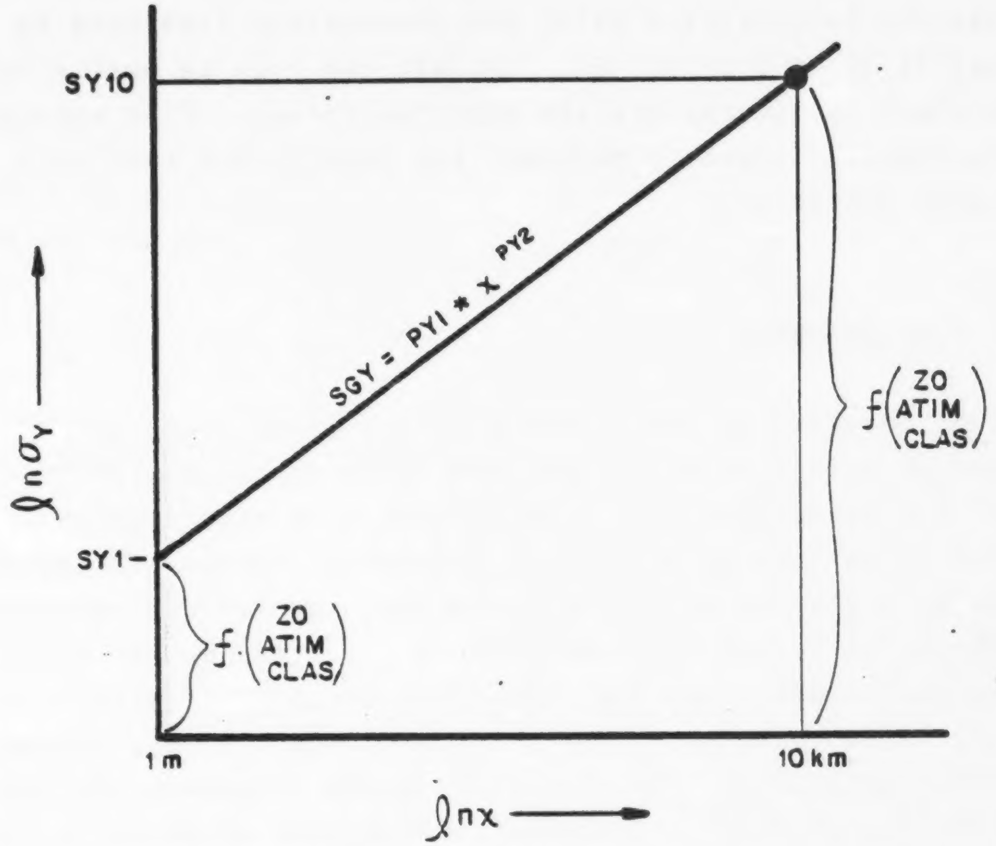
Type of Surface	Z0 (cm)
Smooth mud flats	0.001
Tarmac (pavement)	0.002
Dry lake bed	0.003
Smooth desert	0.03
Grass (5-6 cm)	0.75
(4 cm)	0.14
Alfalfa (15.2 cm)	2.72
Grass (60-70 cm)	11.4
Wheat (60 cm)	22
Corn (220 cm)	74
Citrus orchard	198
Fir forest	283
City land-use	
Single family residential	108
Apartment residential	370
Office	175
Central Business District	321
Park	127

For nocturnal conditions with low mixing heights, wind speeds are likely to be less than 1 M/S. Extremely sensitive wind speed and direction instrumentation would be required for reliable results at such low wind speeds. In order to use CALINE3 for these conditions, measurements of the horizontal wind angle standard deviation will be needed. The model can then be modified to calculate horizontal dispersion parameters based on the methodology developed by Pasquill(15) or Draxler(16). The user is cautioned that the model has not been verified for wind speeds below 1 M/S, and that assumptions of negligible along-wind dispersion and steady state conditions are open to question at such low wind speeds.

Mixing height computations must be made for each element-receptor combination, and thus add appreciably to program run time. As will be seen in the sensitivity analysis, the mixing height must be extremely low to generate any significant response from the model. Therefore, it is recommended that the user bypass the mixing height computations for all but special nocturnal simulations. This is done by assigning a value of 1000 meters or greater to MIXH.

5.4 Horizontal Dispersion Curves

The horizontal dispersion curves used by CALINE3 are identical to those used by Turner(6) except for averaging time and surface roughness power law adjustments similar to those made for the vertical dispersion curves (see Fig. 12). The model makes no corrections to the initial horizontal dispersion near the roadway. The only roadway related alterations to the horizontal dispersion curves occur indirectly by defining the highway width as the width of the traveled way plus 3 meters on each side, and assuming uniform emissions throughout the element.


SY10
SY1–
SGY = PY1 * X PY2
f (ZO ATIM CLAS)
f (ZO ATIM CLAS)
1 m
10 km
ln σY
ln x

ZO = AERODYNAMIC ROUGHNESS
ATIM = AVERAGING TIME
CLAS = STABILITY CLASS
x = PLUME CENTERLINE AXIS
σ_Y = HORIZONTAL DISPERSION PARAMETER
PY1 = exp (SY1)

HORIZONTAL DISPERSION CURVE – CALINE3

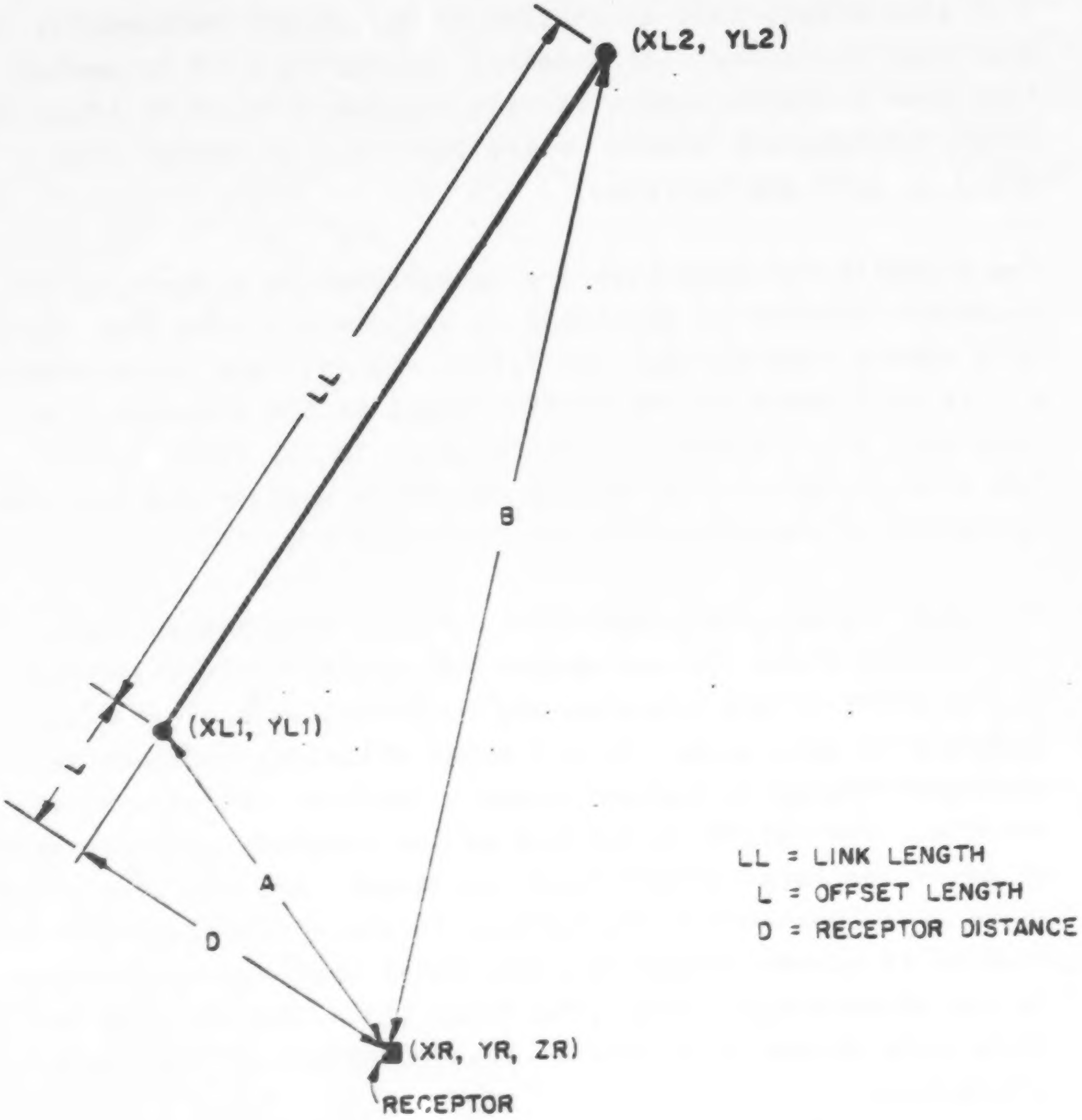
FIGURE 12

If field measurements of the horizontal wind angle standard deviation are available, site specific horizontal dispersion curves can be generated using the methodology developed by Pasquill(15) or Draxler(16). CALINE3 can then be easily reprogrammed to incorporate the modified curves. This approach is recommended whenever manpower and funding are available for site monitoring.

5.5 Site Geometry

CALINE3 permits the specification of up to 20 links and 20 receptors within an X-Y plane (not to be confused with the local x-y coordinate system associated with each element). A link is defined as a straight segment of roadway having a constant width, height, traffic volume, and vehicle emission factor. The location of the link is specified by its end point coordinates (see Fig. 13). The location of a receptor is specified in terms of X, Y, Z coordinates. Thus, CALINE3 can be used to model multiple sources and receptors, curved alignments, or roadway segments with varying emission factors. The wind angle (BRG) is given in terms of an azimuth bearing (0 to 360°). If the Y-axis is aligned with due north then wind angle inputs to the model will follow accepted meteorological convention (i.e. 90° equivalent to a wind directly from the east).

The program automatically sums the contributions from each link to each receptor. After this has been completed for all receptors, an ambient or background value (AMB) assigned by the user is added. Surface roughness is assumed to be reasonably uniform throughout the study area. The meteorological variables of atmospheric stability, wind speed, and wind


(XL2, YL2)
LL
B
(XL1, YL1)
L
A
D
(XR, YR, ZR)
RECEPTOR
LL = LINK LENGTH
L = OFFSET LENGTH
D = RECEPTOR DISTANCE

CALINE3 LINK GEOMETRY

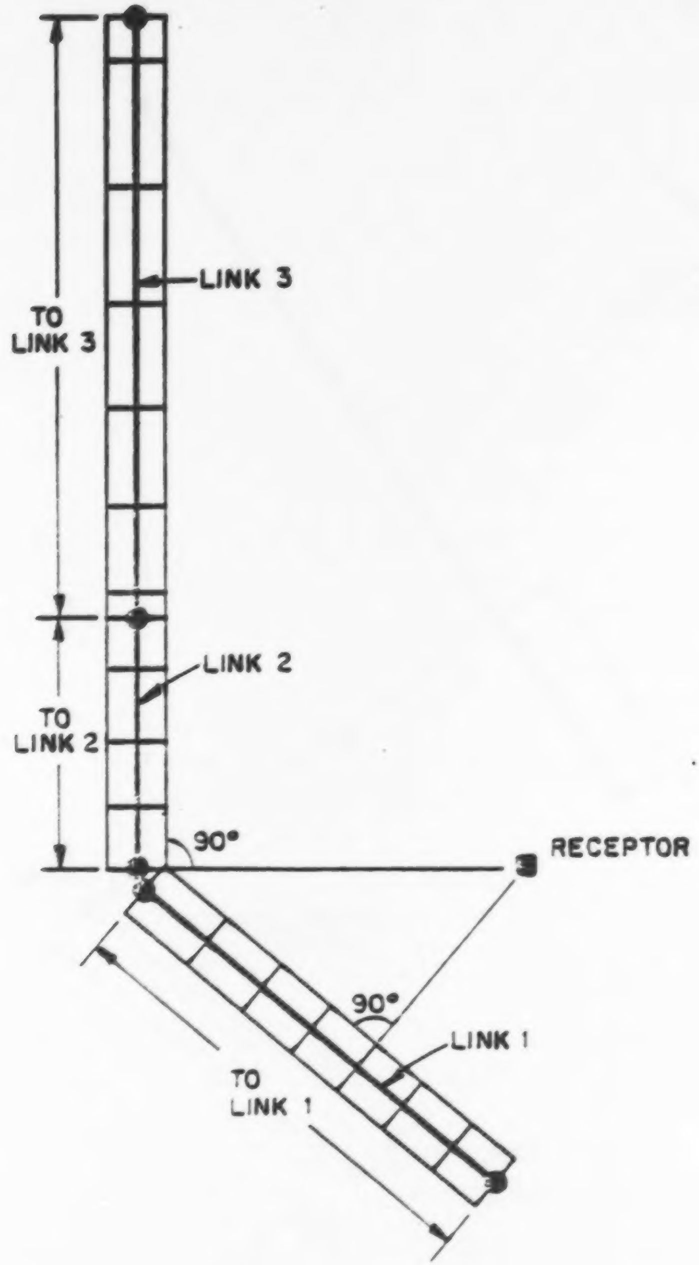
FIGURE 13

direction are also taken as constant over the study area. The user should keep this assumption of horizontal homogeneity in mind when assigning link lengths. Assigning a 10 kilometer link over a region with a terrain induced wind shift after the first 2 kilometers should be avoided. A 2 kilometer link would be more appropriate.

The elements for each link are constructed as a function of receptor location as described in Section 5.1 (see Fig. 14). This scheme assures that the finest element resolution within a link will occur at the point closest to the receptor. An imaginary displacement of the receptor in the direction of the wind is used by CALINE3 to determine whether the receptor is upwind or downwind from the link (see Fig. 15).

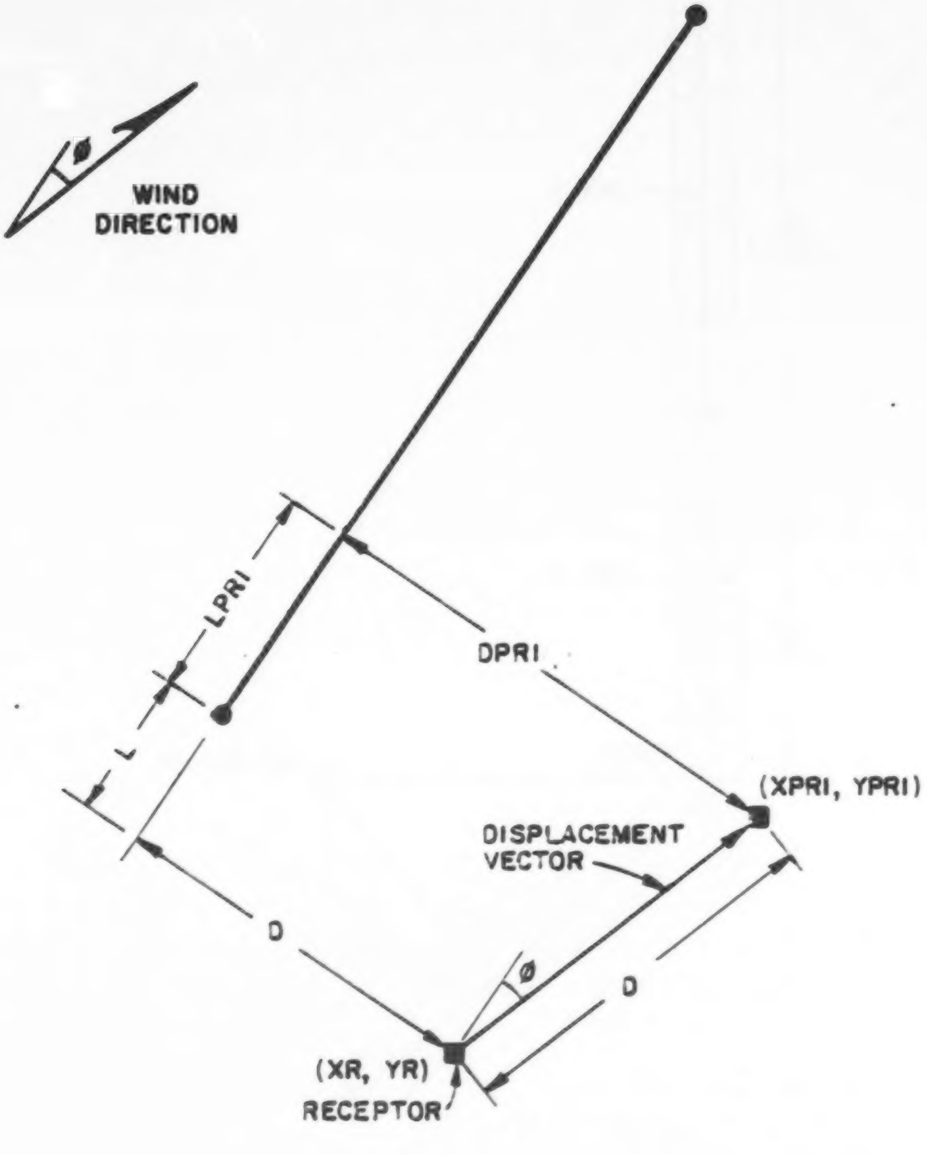
For each highway link specified, CALINE3 requires an input for highway width (W) and height (H). The width is defined as the width of the traveled way (traffic lanes only) plus 3 meters on each side. This 3 meter allowance accounts for the wake-induced horizontal plume dispersion behind a moving vehicle. The height is defined as the vertical distance above or below the local ground level or datum. CALINE3 should not be used in areas where the terrain in the vicinity of the highway is uneven enough to cause major spatial variability in the meteorology. Also, the model should not be used for links with values of H greater than 10 meters or less than -10 meters.

Elevated highway sections may be of either the fill or bridge type. For a bridge, air flows above and below the source in a relatively undisturbed manner. This sort of uniform flow with respect to height is an assumption of the Gaussian formulation. For bridge sections, H is specified as the height of


LINK 3
TO LINK 3
LINK 2
TO LINK 2
90°
RECEPTOR
90°
LINK 1
TO LINK 1

CALINE3 LINK-ELEMENT ASSIGNMENT

FIGURE 14



Ø
WIND DIRECTION
LPRI
L
DPRI
(XPRI, YPRI)
DISPLACEMENT VECTOR
D
Ø
D
(XR, YR)
RECEPTOR

IF DPRI < D THEN D = −D

IF LPRI < L THEN $\begin{cases} UWL = -DWL \\ DWL = -UWL \end{cases}$

IMAGINARY DISPLACEMENT SCHEME USED BY CALINE3

FIGURE 15

the roadway above the surrounding terrain. For fill sections, however, the model automatically sets H to zero. This assumes that the air flow streamlines follow the terrain in an undisturbed manner. Given a 2:1 fill slope (effectively made more gradual as the air flow strikes the highway at shallower horizontal wind angles) and stable atmospheric conditions (suppressing turbulence induced by surface irregularities), this is a reasonable assumption to make(17).

For depressed sections greater than 1.5 meters deep, CALINE3 increases the residence time within the mixing zone by the following empirically derived factor based on Los Angeles data(3):

$$DSTR = 0.72 * ABS(H)^{0.83}$$

This leads to a higher initial vertical dispersion parameter (SGZ1) at the edge of the highway. The increased residence time, characterized in the model as a lower average wind speed, yields extremely high concentrations within the mixing zone. The wind speed is linearly adjusted back to the ambient value at a distance of 3*H downwind from the edge of the mixing zone. By this point the effect of the higher value for SGZ1 dominates, yielding lower concentrations than an equivalent at-grade section.

For depressed sections, the model is patterned after the behavior observed at the Los Angeles depressed section site studied by Caltrans(3). Compared to equivalent at-grade and elevated sites, higher initial vertical dispersion was occurring simultaneously with higher mixing zone concentrations. It was concluded that channeling and eddying effects were effectively decreasing the rate of pollutant transport

out of the depressed section mixing zone. Lower concentrations downwind of the highway were attributed to the more extensive vertical mixing occurring within the mixing zone. Consequently, the model yields higher values for concentrations within or close to the mixing zone, and somewhat lower values than would be obtained for an at-grade section for downwind receptors. Except for these adjustments, CALINE3 treats depressed sections computationally the same as at-grade sections.

It has been suggested that the model could be used for evaluating parking lot impacts. If the user wishes to run the model to simulate dispersion from a parking lot, it is recommended that SGZ1 be kept constant at 1 meter, and that the mixing zone width not be increased by 3 meters on each side as in the normal free flow situation. This is because the slow moving vehicles within a parking lot will impart much less initial dispersion to their exhaust gases.

5.6 Deposition and Settling Velocity

Deposition velocity (VD) is a measure of the rate at which a pollutant can be adsorbed or assimilated by a surface. It involves a molecular, not turbulent, diffusive process through the laminar sublayer covering the surface. Settling velocity (VS) is the rate at which a particle falls with respect to its immediate surroundings. It is an actual physical velocity of the particle in the downward direction. For most situations, a class of particles with an assigned settling velocity will also be assigned the same deposition velocity.

CALINE3 contains a method by which predicted concentrations may be adjusted for pollutant deposition and settling. This procedure, developed by Ermak(18), is fully compatible with the Gaussian formulation of CALINE3. It allows the model to include such factors as the settling rate of lead particulates near roadways(19) or dust transport from unpaved roads. A recent review paper by McMahon and Denison(20) on deposition parameters provides an excellent reference.

Most studies have indicated that CO deposition is negligible. In this case, both deposition and settling velocity adjustments can be easily bypassed in the model by assigning values of 0 to VD and VS.